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A CONTRIBUTION TO THE LIFE HISTORY OF *CASUARINA*

By B. G. L. Swamy

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A CONTRIBUTION TO THE LIFE HISTORY OF *CASUARINA**

By B. G. L. Swamy

(*Harvard Biological Laboratories, Cambridge, Mass.*)

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Introduction

The genus *Casuarina* Linn. consists of about 35 species distributed chiefly in Australia and Polynesia (Willis, 1931). From its center of origin it has migrated to regions of greater humidity and heat, tropical or equatorial, such as New Caledonia and the islands of the Asiatic Archipelago. Of all the species of this genus only *C. equisetifolia* Forst. actually possesses an extended distribution, which comprises all the lands about the Indian Ocean. In India, it occurs in a wild state on the eastern side of the Bay of Bengal (Hooker, 1894). Owing to its fast-growing nature, its capability for growing on coastal areas, and the importance it has in the reclamation of sand dunes, it has become one of the prominent cultivated trees elsewhere, especially on the Coramandel and Kanara Coasts (Gamble, 1922). In the interior, it is grown mainly for fuel; recently, the tall trunks have begun to be used as poles and rafters and hence have attained an economic status. Two other species, *C, suberosa* Ott. & Dietr. and *C. stricta* Ait, which have been introduced into India, are less successful and are restricted to small areas in the Nilgiris, where they are grown in plantations at an elevation between 5000 and 7000 feet.

*Contribution from the Biological Laboratories, Harvard University, Cambridge 38, Massachusetts. Introduced by I. W. Bailey and R. H. Wetmore.

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There is some difference of opinion regarding sex expression in *C. equisetifolia.* Hooker (1894) has called it "dioecious (?)"; but according to Brandis (1906), it is monoecious and "male and female flowers are sometimes found on the same branch, but, (as often happens with monoecious trees) some trees habitually bear male flowers, others female only." Rendle (1938) also says that the plant is monoecious. In plantations near Bangalore (India), however, dioecism is the prevailing type of sex expression and monoecism is rare.

The staminate flowers are borne in terminal spikes on short lateral branches. The internodes of the inflorescence axis are very short and at each node the bracts fuse to form a cup, with several flowers hanging out over its edge. Each of these flowers has two bracteoles representing the outer perianth and two membranous and transparent flap-like structures, placed at right angles to the former, representing the inner perianth. The filament originates from the base of the inner whorl and bears at its tip a single anther with four loculi (figs. 1–4). The female flowers are borne in dense globular or oblong heads. Each flower lies in the axil of a bract and has two bracteoles (figs. 5–7). The ovary is flattened laterally and consists of two fused carpels, with the posterior loculus empty and the anterior alone containing two ovules. The long and bifid stigma hangs out beyond the other floral parts.

In monoecious plants, the male flowers are borne towards the apex of lateral branches and the female cones in the axils of the latter.

Pollination is accomplished by the agency of wind during the months of September and October. As the fruit ripens, the two bracteoles, which are somewhat hairy during the early stages, develop into two large woody valves. The fruit is a one-seeded winged nut, the embryo completely filling the seed cavity. The seeds are disseminated during the months of January and February of the succeeding year.

Previous Work on the Genus

The first and the most important contribution on the embryology of *Casuarina* was published by Treub in 1891. The species investigated by him in greatest detail was *C. suberosa;* but a few stages in the development of two other species, *C. Rumphiana* and *C. glauca,* were also studied. He reported several unique features, the most significant of them being the origin of the basal part of the sporogenous tissue from cells not belonging to the archesporium but to the chalaza; the transformation of some of the cells of the sporogenous tissue into tracheids, a feature recalling the formation of elaters in certain liverworts; the simultaneous development of a score of embryo sacs to

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maturity; the absence of antipodals; the formation of as many as fifty endosperm nuclei before fertilization; and the remarkable phenomenon of chalazogamy.

Some of Treub's observations were, however, so unexpected that in reviewing them Chamberlain (1896) suggested a study of the genus "in much greater detail, in order that Treub's conclusions may receive additional confirmation or be rejected."

Juel (1903) studied the development of the megaspores in *C. quadrivalvis* and an undetermined species collected from Algeria. In both species he demonstrated the formation of normal megaspore tetrads and also gave a rough estimate of the number of chromosomes saying that it was not less than eight and not more than twelve in the gametophytic cells. In addition, he drew attention to certain kinoplasmic bodies lying near the poles of the spindles during tetrad formation, which resemble the dense areas described in various gymnosperms. Though he did not pursue his observations to the later stages, he regarded the development of the embryo sac, the course of the pollen tube, and the stages in the formation of the embryo as conforming with the description of Treub.

Frye in 1903 gave an account of the development of the embryo sac (up to the time of fertilization) in *C. stricta*. He found that the development of the female gametophyte is quite normal and that the polar nuclei never form any endosperm before fertilization. He confirmed the presence of chalazogamy, but the course of the pollen tube within the nucellus and the exact place where its contents are discharged into the embryo sac were not studied by him.

As no work has been done during the last 45 years and as many of the features in its embryology are still obscure, it appeared to me that a fresh study was desirable.

Material and Methods

Material for the present investigation was collected from the *Casuarina* plantations near Bangalore. Formalin-acetic-alcohol and Allen's modification of Bouin's fluid were used for fixation. The usual method was followed for dehydration and infiltration and sections were cut serially with a sliding microtome. Heidenhain's iron-alum haematoxylin with a counterstain of light green or eosin in clove oil was used for staining.

To follow the course of the pollen tube, the following method was found useful: fresh carpels were dissected out and boiled in water for two minutes. They were then run up to pure glycerine through four stages, at an interval of two hours between each stage, in a thermostat

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maintained at 52° C. The carpels were then mounted in lactophenol, which was slightly colored with aniline blue or safranin. The wall of the pollen tube absorbed these stains well and stood in sharp contrast with the rest of the tissue, making it possible to follow its course into the nucellus and embryo sac.

Observations

Casuarina equisetifolia

(1) *Microsporangium and male gametophyte.*—A transverse section of a young anther shows that the four groups of archesporial initials differentiate at an early stage, one at each corner. Each group is hypodermal in origin and consists of two or three cells as seen in transverse sections. The number of such cells as counted in longitudinal section varies between ten and fifteen per loculus.

The archesporial cells divide periclinally to form two layers (fig. 12); subsequent divisions of the outer or primary parietal layer result in about three or four layers of cells (fig. 13, 14). Of these, the outermost layer transforms itself into the endothecium and the innermost into the tapetum. The former develops the characteristic banded thickenings at maturity (fig. 16). The tapetal cells are sometimes binucleate (fig. 15).

The nuclei of the microspore mother cells undergo the usual prophasic changes of the two meiotic divisions to form tetrahedral tetrads. After a period of rest and the laying down of the exine and intine, the microspore (fig. 17) divides (fig. 18) to form two unequal cells, the larger vegetative and the smaller generative (fig. 19). Although spindle-shaped at first, the generative cell later assumes a spherical form and is seen to lie inside the cytoplasm of the vegetative cell (fig. 20). The mature pollen grain has a thick exine with three germ pores distributed equidistantly on the equator. This is the shedding stage of the pollen.

(2) *Ovary and ovule.*—The earlier development of the ovary reveals that it arises as a cup-shaped invagination of the thalamus. The edges of the cup converge, thus enclosing a cavity within. Above this point, the edge of the cup bifurcates and the two halves extend out of the bract in the form of solid filiform appendages, which are the stigmas (fig. 5, 6). After pollination is accomplished, the portion of the ovary enclosed within the bract expands and flattens and the stigmas dry up (fig. 8). The other histological changes which follow pollination will be considered later.

A very young ovary is represented in figure 9. It has two carpels

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of which only one is fertile and the other aborts (see figs. 10, 11). Two epitropous[1] ovules originate in the former from the placenta. The inner integument, which is thinner (2–3 layers thick in the region of the micropyle, fig. 23), arises first but eventually becomes crushed between the outer integument and the nucellus, except in the region which forms the micropyle.

(3) *Megasporangium.*—At the time of origin of the two integuments, a plate of 5–7 hypodermal cells becomes differentiated as the archesporium. A longitudinal section of the nucellus at about this stage is represented in figure 21, which shows three such cells. Each of these cells divides periclinally to form a primary parietal and a primary sporogenous layer.

The primary parietal layer divides periclinally as well as anticlinally to form 5–6 layers of wall cells, as a consequence of which the sporogenous mass is pushed deeper into the nucellus. During this period, the primary sporogenous cells also undergo repeated divisions so as to constitute a compact mass of 40–50 cells occupying the axial region of the nucellus (fig. 23).

Meanwhile a procambial strand becomes differentiated in the chalaza. To begin with, this strand is merely an extension of the provascular trace supplying the placenta; later it extends upward into the center of the mass of sporogenous cells (fig. 22, 23). It may be noted that certain centrally situated cells of the sporogenous mass also seem to contribute towards the extension of the strand. In the early stages, the cells of the strand are distinguishable only by their elongated appearance, but by the time of fertilization such of the cells of the strand that lie outside the nucellus develop into vascular elements (figs. 32, 38). The nucellar cells which lie in continuation with the strand, however, become disorganized at the time when the embryo sacs send out antipodal caeca.

After the divisions of the primary sporogenous tissue, the resultant cells elongate and function as megaspore mother cells. Each megaspore mother cell shows the typical prophasic stages of meiosis and forms dyad cells (fig. 24), which in turn complete the second meiotic division to form a linear tetrad of megaspores (fig. 25).

Quite normally more than one megaspore of a tetrad begins further development. There is no definite rule as to which megaspore or megaspores should continue development; one, two, three or occasionally all the four may develop further. Some may develop only up to the two- or four-nucleate stages but others proceed right up to the eight-nucleate stage although the nuclei may not always become

[1] See B. D. Jackson's "A Glossary of Botanic Terms," 1900, London, p. 92.

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organized into the various components of the embryo sac. In figure 27 all the megaspores of two adjacent tetrads have developed to the eight-nucleate stage. As many as 15–20 well organized embryo sacs are frequently present in the same nucellus (fig. 32).

At the two-nucleate stage the embryo sac usually begins to elongate towards the chalaza in the form of a long narrow tube (figs. 26–29). This tube or caecum forms a large terminal pouch at its lower extremity (figs. 31, 32). The initiation of the caecum may sometimes be postponed to the four- or even the eight-nucleate stage (fig. 30).

It may be recalled here that the ovary contains two ovules. Both of these develop together until the megaspore tetrad stage, The further development of an ovule is related to the presence of the pollen tube. The ovule which does not receive a pollen tube becomes arrested and is eventually crushed by the growth of its fellow.

The egg apparatus exhibits a variety of forms. The synergids may be hooked and have the usual basal vacuoles (figs. 33, 34), or they may look very much like the egg (fig. 35). In the latter case, they show an apical vacuole with the cytoplasm and nucleus lying towards the base. All these variations are often present in the embryo sacs belonging to the same nucellus. The polar nuclei are usually found attached to each other just below the egg apparatus, although sometimes they may occupy a different position in the embryo sac. The antipodals do not form cells and lie in the basal end of the caecum (figs. 31, 32).

(4) *Pollen tube.*—Pollination takes place during the months of September and October. The bifid and filiform stigmas secrete a mucilaginous substance which catches the pollen grains (fig. 36). The latter begin germination on the stigma within three to four days after pollination. The growth of the pollen tube is completely intercellular. It travels through the stigma, partly digesting the adjacent cells which are richly packed with nutritive materials. Occasionally the tube sends out short, blind branches towards the free end of the stigma (fig. 36).

As the tube leaves the stigma and enters the style, the former begins to dry up and wither away. The further course of the pollen tube is shown in figure 37, which is a sagittal section of the pistil of *C. equisetifolia.*

In the style, the pollen tube travels through the central region, where the cells are greatly elongated. This region is continuous with the ovule through the "bridge"[2] (see figs. 10, 11, 37, 38). It then

[2] For the sake of description, this term is used in the present paper to denote the tissue connecting the upper portion of the ovule with the ovary, so that the apex of the ovule is continuous with the style.

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enters the chalazal region of the ovule. Here, another unique feature is presented. After arriving at this point, the pollen tube sends out several branches which end blindly. The manner of branching and the number of branches given out are not constant. The pollen tube represented in figure 38 (reconstructed from six serial sections) may be considered as typical. Some of the branches reach the outermost layers of cells of the outer integument towards the base; and while doing so, find their way between the chalazal pouches of the embryo sac caeca.

The particular branch of the pollen tube which contains the sperms makes its way between the caeca into the nucellus. Here the lumen of the tube becomes slightly expanded and its wall appears to be thicker. It absorbs such stains as eosin, erythrosin, and fast green with great avidity and therefore stands out sharply from the other tissues. Making its way upward between the embryo sacs, it reaches the upper end of one of them lying nearest to the micropyle (fig. 38).

(5) *Fertilization.*—The generative cell divides in the pollen tube before the latter enters the chalaza. The two sperm nuclei are each surrounded by a globular cytoplasmic sheath but no cell wall or enclosing membrane could be made out. The vegetative nucleus and the two sperms are always seen together, the former being sometimes slightly ahead of the sperms. Figure 40 represents the tube nucleus and the two male cells in the tip of a pollen tube which was on its way upward to the micropylar end of an embryo sac inside the nucellus.

The pollen tube enters the embryo sac at a point close to the egg apparatus and discharges the sperms. At this time the cytoplasmic sheath around them is not distinguishable.

One of the sperm nuclei fuses with the egg nucleus which is nearly two or three times larger than the former. It appears, however, that after a short time the second sperm nucleus undergoes some increase in size (fig. 39; note the difference in size between the sperm nucleus in contact with the polar nuclei and that inside the egg).

(6) *Endosperm.*—The fertilized embryo sac enlarges greatly in size while the unfertilized ones degenerate and disappear. This is clearly seen in figure 41, in which there is a fertilized sac with the endosperm nuclei in division and at its base, a small unfertilized sac on its way to disappearance.

The primary endosperm nucleus begins to divide soon after triple fusion is complete. All the early divisions take place in the micropylar part of the embryo sac. The daughter nuclei then move towards the periphery of the sac and continue further divisions, which gradually extend towards the chalazal region (fig. 42).

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Wall formation commences at the micropylar end of the sac and proceeds centripetally as well as towards the chalaza. It is very common to find endosperm cells at the micropylar end and actively dividing nuclei at the chalazal end of the same embryo sac (fig. 43).

Broadly speaking, the endosperm may therefore be said to develop in four stages:

(a) During the early divisions, the spindles are evanescent and a large number of free nuclei are formed (fig. 42).

(b) In the second phase, free nuclear divisions cease in the micropylar region and wall formation commences from this end (fig. 43). The nuclei in the chalazal region continue to divide, however, and the spindles that are formed during these divisions tend to persist for a fairly long time.

(c) In the next stage, free nuclear divisions cease entirely and regular cell divisions begin. The endosperm enlarges to such an extent that almost all the nucellar cells are disintegrated and crushed.

(d) Finally, there is a still further increase of the endosperm tissue at the micropylar end, brought about by the divisions of the first-formed endosperm cells. This stage commences when the embryo is at about the quadrant phase (fig. 45), and the divisions are at a peak at the time of the differentiation of the cotyledons. Thus, when the embryo is passing through a highly metabolic stage and is rapidly absorbing the surrounding tissue, the endosperm cells by continuous divisions keep up a supply of nutritive tissue for the embryo.

The final result of these stages in the development of the endosperm is the formation of a massive tissue which occupies the entire seed cavity; the smaller-sized and more compactly arranged cells of the micropylar region gradually grade into the larger and considerably loosely packed cells towards the chalaza. At this stage, only one or two layers of the nucellus can be made out at the micropylar end (fig. 49), but even these become disorganized during the later stages of embryogeny.

(7) *Embryo.*—The fusion of the sperm and the egg nuclei is completed only after four to eight endosperm nuclei are formed. The zygote divides after the commencement of the second step in the endosperm development when wall formation has taken place in the micropylar region.

The first division of the zygote is transverse (fig. 43). The basal cell divides by another transverse wall to form a row of three cells (fig. 44). The cell next to the micropyle does not divide further but becomes enlarged and vacuolated (figs. 44–48); in later stages, its nucleus is slightly hypertrophied. The middle cell forms a row of

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four to six suspensor cells arranged in a linear manner (figs. 45–48). The terminal cell divides longitudinally (fig. 45). Further divisions give rise to the quadrant (fig. 46) and octant stages and later a globular mass of cells is produced as shown in figures 47 and 48. This is followed by the differentiation of the cotyledons, radicle, and plumule (figs. 49–51).

During its later development the embryo digests all the endosperm so that it eventually occupies the entire cavity of the seed and is covered only by the shrivelled integuments. The cells of the embryo become loaded with starch grains and in even greater proportions with certain globular particles which take up a very deep stain with haematoxylin and osmic acid.

(8) *Pericarp.*—In the early stages, the ovary wall consists of homogeneous cells without much differentiation, but as development continues, it undergoes some interesting modifications.

Figure 55 shows a longitudinal section of a fruit at about the octant stage of the embryo. The inner four to eight layers of the ovary wall towards the micropylar region of the ovule (*c* in fig. 55; also fig. 38) represent the crystalliferous tissue whose cell walls become enormously thickened and whose cell contents become replaced by a single large polygonal crystal. In the walls of these cells develop innumerable ramified pits (fig. 56) which are continuous with those of the adjacent walls. The probable function of these layers is to afford protection to the developing embryo in addition to that provided by the two woody bracts.

The cells lying next to the crystalliferous tissue become elongated in the direction of the long axis of the ovary (*b* in fig. 55). They lose their protoplasts and the walls develop spiral thickenings (fig. 57). Ultimately the whole of this tissue assumes a spongy texture and the radicle of the embryo lies in close contact with it. Probably it serves to absorb and store moisture during the germination of the seed.

(9) *Abnormalities.—Double nucelli.* The material gathered from one particular tree in a *Casuarina* plantation had invariably two nucelli in its ovules (fig. 52). These nucelli were of unequal sizes, although both occurred within common integuments. In each nucellus the development proceeds as described for normal ovules, but the number of embryo sacs formed in the larger nucellus varies between eight and twelve, whereas in the smaller nucellus it ranges from five to eight. After the embryo sac in one nucellus has been fertilized, the other nucellus degenerates.

Supernumerary pollen tubes. Though many pollen grains germinate on the stigma, as a rule only one pollen tube succeeds in reaching the

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nucellus. Only exceptionally did more than one pollen tube enter the same nucellus (figs. 59–61) and the maximum number observed was three. All the pollen tubes enter the nucellus through the chalaza, i. e., by the chalazogamous method typical of the genus. In fig. 59, showing three pollen tubes, their distal portions have become entangled over the micropylar end of an embryo sac, perhaps as a result of competition (see also fig. 59 *a*). However, no healthy or normal sexual nuclei were noticed in any of them.

In figure 60 the first pollen tube has fertilized the uppermost embryo sac in the nucellus and the endosperm is already at the four-nucleate stage. A second pollen tube in the same nucellus has reached the apex of another embryo sac but has not yet discharged its contents and the two sperm nuclei are clearly visible at its tip.

Polyembryony. Occasionally when two embryo sacs are fertilized there is a possibility of polyembryony. Figure 61 shows two pollen tubes associated with two embryo sacs, both with free nuclear endosperm. It may be inferred that seeds formed from such ovules may have two embryos.

Some ovules had two two-celled proembryos in the endosperm (fig. 53). Since there was no evidence of the entry of more than one pollen tube, the exact nature of the origin of such plural embryos remains undetermined.

In another ovule represented in figure 54, the sexually produced embryo consists of a basal cell, four suspensor cells, and the terminal embryonal mass. On the right side of this embryo, another cell, probably derived from the nucellus, has pushed into the endosperm and has undergone some free nuclear divisions. There is a possibility that this might later develop into an asexual embryo. However, this view is open to some doubt, since nucellar embryos are not known to develop from a free-nucleate cell.

A study of germination of the seeds collected from some of the *Casuarina* plantations showed two or rarely three polyembryonate seeds in every hundred. As a rule, not more than two seedlings were obtained from any seed and one of them was always smaller than the other.

Parthenocarpy. In one isolated female tree (with no other plant of the same species lying within a two mile radius of it), the development seemed to get arrested at the megaspore tetrad or two-nucleate embryo sac stage; yet fruits formed on the tree and appeared quite normal. A histological examination showed that these fruits were very similar to those from other trees but germination tests of the seeds gave only negative results. It is possible that the parthenocarpic development of the ovary is induced by the germination of

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foreign pollen but the ovules fail to produce embryos owing to the lack of fertilization.

Placenta. Certain ovules showed an abnormal development of the placental tissue in comparison with the size of the two ovules (fig. 62; compare the normal ovary shown in fig. 37). The cells of such abnormal placentae were found to be devoid of cytoplasm and their walls had numerous bordered and semibordered pits (fig. 62 *a*). Fertilization followed by embryo formation up to the octant stage was seen to take place normally in the ovules developed on such placentae but no further stages could be followed and the significance of this behavior of the placenta remains to be studied.

Casuarina montana

The seeds of this species were obtained from Malaya in 1940. They were germinated and the seedlings transplanted to a place isolated from the *C. equisetifolia* plants. The trees began to bear flowers from the fourth year onwards and produced viable seeds. The following observations are based on material collected from the above plants.

(1) *Ovary and ovules.*—The ovary is bicarpellary but only one of the carpels is fertile. This contains two ovules. During early stages, their axes are more or less at right angles to the longitudinal axis of the ovary (fig. 63), but later become so oriented that the micropyle points towards the style (fig. 64). On the side towards the placenta, the outer integument is fused with the placental tissue to form the bridge which serves for the passage of the pollen tube from the base of the style to the chalaza.

(2) *Megasporogenesis and female gametophyte.*—The archesporium differentiates as a group of three or four hypodermal cells, each of which divides periclinally to form the primary wall cells and the primary sporogenous cells. The former divide to give rise to seven or eight wall layers; the latter divide to form a massive sporogenous tissue.

A point of special interest in this species is that while the sporogenous cells in the upper part of the nucellus are differentiating into megaspore mother cells, those in the lower part continue to divide actively for some time, adding to the sporogenous tissue. Proceeding from the basal part upwards, one can see a series of stages in megasporogenesis and megagametogenesis in the same ovule (fig. 66).

The extension of the procambial strand of the funiculus into the chalaza and thence into the nucellus takes place in the same way as described for *C. equisetifolia* (figs. 63–66). The cells of the procambial strand lying within the nucellus do not become tracheidal at any

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stage of development but completely degenerate while the embryo sac caeca are developing.

The megaspore mother cell enlarges and elongates appreciably before undergoing the meiotic divisions. A linear tetrad of megaspores is formed. All the megaspores show a tendency towards further development to varying extents, although occasionally one or more of them degenerate at an early stage. The mature embryo sac has the usual organization except that the antipodals are ephemeral. The synergids sometimes have an egg-like appearance with apical vacuoles and basal nuclei (fig. 68). The polar nuclei fuse before fertilization and the secondary embryo sac nucleus lies just below the egg apparatus (fig. 67).

Only from three to five embryo sacs in a nucellus usually attain a fertilizable condition, the rest degenerating at an earlier stage. Embryo sac caeca are formed as in *C. equisetifolia.*

The structure of the ovule at the time of fertilization is interesting in this species. The nucellus pushes itself beyond the integuments through the micropylar end and comes to lie exposed in the ovary (figs. 65, 66). This situation is a result of the prolonged divisions of the primary archesporial cells towards the chalaza.

(3) *Fertilization.*—The pollen grains are two-celled at the time of shedding and pollination is accomplished by wind during the months of September and October. As in *C. equisetifolia*, the pollen tube enters the chalaza through the bridge and sends out numerous blind branches at the chalaza (figs. 69–71), some of which show a tendency to pass out to the superficial cell layers of the ovule.

The nucleus of the generative cell divides in the pollen tube into two sperms. They are surrounded by cytoplasmic sheaths (figs. 71, 72) but no trace of a cell wall or limiting membrane could be made out. The sperms are always associated with the tube nucleus (figs. 70–73).

The vegetative nucleus and the sperms do not enter any of the blind branches of the pollen tube but remain in its subterminal part and eventually pass into the particular branch which grows up into the nucellus. Here, the lumen of the tube expands and the wall thickens slightly. After passing between the antipodal caeca of the embryo sacs, the pollen tube reaches the micropylar tip of one of the sacs. At this point the pollen tube pierces the embryo sac and discharges its contents into it. Actual stages in double fertilization were not seen. The earliest stage observed after fertilization (fig. 76) showed the course and the remains of the pollen tube, the zygote and four endosperm nuclei. The persisting synergid had two nuclei.

Many pollen tubes show abundance accumulation of starch grains while they traverse the chalaza and nucellus.

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(4) *Abnormalities.*—Figure 74 represents a pollen tube which behaved in an abnormal manner. After entering the nucellus, it passed out of the nucellus and then recurved toward the chalaza, the tip of the tube penetrating between the inner integument and the nucellus. The tip of this pollen tube contained the sperms and the vegetative nucleus (fig. 72). In the nucellus of this ovule, one embryo sac had attained maturity but degeneration had already set in.

Another abnormality relates to a peculiar branching of the pollen tube after it had reached the top of an embryo sac. It gave rise to many short branches which hung on the top of the embryo sac in a drooping manner. One of the branches contained the vegetative nucleus and sperms (fig. 73). It is interesting to note that before reaching the micropylar end of the embryo sac, this pollen tube had wound around the embryo sac (fig. 75), which was itself in a state of degeneration.

Chromosome Number

In the cells of the root tips of both species studied at present eighteen chromosomes were seen (figs. 58, 77).

Comparisons with Other Species of Casuarina

(1) *Microsporogenesis.*—The present study is the first to give an account of the development of pollen in *Casuarina.* The archesporium differentiates from a group of hypodermal cells. The primary parietal cells produce the endothecium, one or two middle layers, and a tapetum. The primary sporogenous cells function directly as the microspore mother cells, which give rise to microspores. The pollen grains are shed at the two-celled stage.

(2) *Ovary and ovules.*—The wing-like expansion of the ovary, the crystalliferous and sclerosed cells occurring in its inner cell layers, and the lateral origin of the epitropous ovules from the placenta are features common to all species so far investigated. Attention may however, be drawn here to the figures 6, 7 and 8 of Poisson (1871), illustrating a few stages in the development of ovules in *C. equisetifolia.* A study of these figures give the impression that the two ovules originate from the base of an unilocular ovary although Poisson does not refer to this point in the text. Actually, the ovules arise laterally from the placenta and become erect during their subsequent growth, as is demonstrated in the present paper.

The two integuments arise more or less simultaneously. The micropyle is erect in all species excepting *C. equisetifolia,* in which

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sometimes it is slightly bent or curved. In *C. montana*, a micropyle is absent during later stages, as the upper part of the nucellus pushes itself out of the two integuments and comes to lie exposed in the ovary at the time of fertilization.

(3) *Conducting strand.*—A procambial conducting strand becomes organized in the chalazal region of the ovule in both the species studied by me. This continues upwards into the nucellus as a central core, surrounded at its tip by the sporogenous cells. Some of the latter themselves seem to elongate and partially contribute to the extension of the strand, instead of functioning as megaspore mother cells. However, the cells were not seen to become tracheidal at any time of their development, although those outside the nucellus developed the usual spiral thickenings by the time of fertilization.

A detailed study of Treub's illustrations seems to indicate that a similar conducting strand is also present in the species investigated by him. His plate 16, figures 1–4 show beyond doubt that the conducting strand extends up to the base of the nucellus. He reports that in *C. glauca* and *C. Rumphiana* some of the archesporial cells themselves become transformed into tracheids (see his plate 19, figures 2, 3, 5; and plate 20, figures 2, 5, 6, 7). In other species, however, viz. *C. suberosa* (Treub, 1891), *C. stricta* (Frye, 1903), *C. equisetifolia*, and *C. montana* (present study), such a transformation seems to be absent.

(4) *Sporogenous tissue.*—In *C. suberosa*, according to Treub, several hypodermal cells ("primary mother cells") begin dividing periclinally and become buried in the nucellus; the limits of this tissue are more clearly defined towards the micropyle and the sides but not towards the chalaza. In this region, owing to the presence of a strong "intercalary growth", Treub was induced to suspect that the lower portion of the sporogenous tissue arose secondarily from cells which do not belong to the primary archesporium.

Frye (1903) noted that in *C. stricta*, the cells of the hypodermal archesporial tissue divide periclinally to give rise to the primary wall cells and primary sporogenous cells. He did not observe any "intercalary growth" at the base of the nucellus and considered that there was no other method of the origin of the sporogenous tissue than from the primary archesporium. Juel's (1903) work on *C. quadrivalvis* and the present study on *C. equisetifolia* confirm this. *C. montana* is similar but has another interesting feature in that the sporogenous tissue continues to increase in bulk by the intercalary divisions of the primary sporogenous cells themselves, so much so that the major portion of the nucellus becomes pushed out of the integuments.

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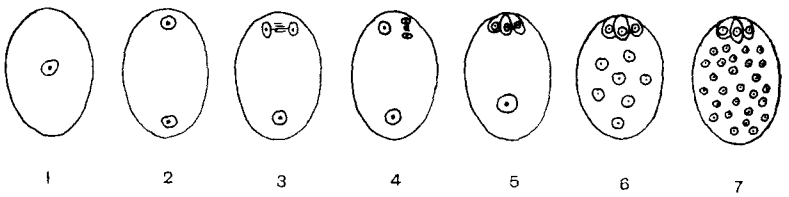
Perhaps a similar phenomenon, to a lesser degree, exists in *C. suberosa*, which led Treub to suspect that some of the sporogenous cells situated towards the chalaza might have arisen from cells other than those belonging to the primary archesporium.

(5) *Female gametophyte.*—According to Treub, the primary chalazal nucleus of the binucleate embryo sac remains at rest for some time while the other divides immediately into two. Frequently one of these divides again so that a group of three nuclei is formed at the micropylar end. These become surrounded by cytoplasm and individual cellulose membranes and constitute the egg apparatus. After this, the primary chalazal nucleus is said to undergo a number of free nuclear divisions, resulting in as many as 50 nuclei, which constitute the endosperm. It is at about this stage that the embryo sac is said to be ready for fertilization. The gist of his observations is diagrammatically represented in the figure below:



Several of the embryo sacs developing in a nucellus may send out chalazal prolongations. Only one of them (the "fertile macrospore") is, however, said to develop the egg apparatus and endosperm nuclei and attain a fertilizable condition. The other embryo sacs ("sterile macrospores") do not develop to this stage, being devoid of an egg apparatus but having one or two nuclei.

Other unusual features mentioned by Treub are the absence of antipodals and the anomalous position of the egg apparatus, frequently seen at a considerable distance below the apex of the embryo sac.

Juel (1903) studied *C. quadrivalvis* but his observations do not go beyond the tetrad formation. Frye (1903) made a more detailed study which, together with my own observations, enable us to draw the following conclusions:

(i) There is a linear tetrad of megaspores formed and usually more than one megaspore of the tetrad continues further development.

(ii) The embryo sac is of the monosporic eight-nucleate type and

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consists of an egg apparatus (one egg and two synergids), two juxtaposed polar nuclei and three ephemeral antipodal nuclei.

(iii) Of the many enlarging megaspores in a nucellus, as many as a score or so develop into normally organized embryo sacs. Others become arrested in their development. Treub's distinction of the embryo sacs into "fertile" and "sterile" is incorrect and misleading. As a rule, it is one of the two or three embryo sacs that are situated in the upper part of the nucellus which becomes fertilized.

(iv) Almost all the embryo sacs in a nucellus form the antipodal caeca.

(v) Endosperm formation does not occur in unfertilized embryo sacs.

(6) *Course of the pollen tube.*—The most remarkable feature in *Casuarina* is the chalazogamous route taken by the pollen tube to reach the egg apparatus. Treub was the first to discover this phenomenon and his description may be briefly stated as follows.

The pollen tube proceeds from the style into the bridge which joins the upper part of the ovule with the placenta in continuation of the style. From here, it proceeds downwards to the end of the vascular bundle which terminates in the chalaza. After giving out one or two short branches, it now continues onward into the chalaza and the nucellus, finally passing up to the embryo sacs. The passage of the pollen tube into the nucellus is facilitated by the "tails" of the macrospores which have digested much of the tissue lying in its path in the chalaza.

In referring to the entry of the pollen tube into the embryo sac, Treub repeatedly says that the tip of the pollen tube does not apply itself against the embryo sac membrane at the point where the egg apparatus is situated but at the opposite end, suggesting thereby that it discharges its contents into the embryo sac somewhere at the basal end of the embryo sac. Frye's observations on the pollen tube course in *C. stricta* do not throw more light on the matter. He agrees that the pollen tube enters the chalaza through the bridge and that it gives out some branches in this region, but he is not definite about its further behavior and writes, "I doubt whether there is any fixed path within the nucellus for the tube."

In this respect my observations on *C. equisetifolia* and *C. montana* may be summarized as follows:

As in the previously investigated species of *Casuarina*, the pollen tube enters the base of the ovule by passing through the bridge. Upon entering the chalaza, it invariably sends out branches. That branch which contains the sperm nuclei proceeds upward into the nucellus through the spaces *between* the vesicular swellings of the

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embryo sac caeca and finally reaches the micropylar end of an embryo sac (usually occupying the uppermost position in the nucellus). No pollen tube was seen to enter at the basal end of an embryo sac and travel *through* its cavity.

Regarding the attachment of the pollen tube to the wall of the embryo sac, Treub emphasizes that this occurs at a point far away from the egg apparatus. In the present investigation, however, the pollen tube always was seen to implant itself on the embryo sac only at the point of situation of the egg apparatus, which is organized always at the micropylar end of the sac.

It will not be out of place here to call attention to some incorrect versions of Treub's work. Thus, Oliver (1895) writes: "From the base of the ovule *the pollen tube penetrates towards the apex of the ovule, reaching the egg cell from below,* not from above as in the cases in which the pollen tube entered the ovule by the micropyle". Coulter and Chamberlain (1903), in referring to figure 2, plate 22[3] of Treub's paper (their fig. 67 a) remark that the pollen tube "becomes associated with the numerous elongated sterile megaspores; and doubtless they are of service in rendering the passage easy; *later it enters the antipodal region of the embryo sac and approaches the egg apparatus from that direction*". Willis (1931) observes that "it (the pollen tube) passes upwards *inside a sterile macrospore* and finally enters the fertile one." Rendle (1938) also speaks of the pollen tube as ". . . . often passing up the caecum of an embryo sac."[4]

A careful perusal of Treub's writing shows, however, that nowhere does he speak of the pollen tube actually entering an embryo sac through its basal end and travelling inside its cavity to discharge its contents below the egg apparatus. As has already been stated, according to him, the pollen tube touches the embryo sac at a place far away from the place of insertion of the egg apparatus and discharges its contents from such a point of contact, so that the male gametes will have to travel a considerable space inside the embryo sac in order to reach the egg and polar nuclei.

(7) *Branching of the pollen tube.*—It is a very common feature in the genus *Casuarina* to find the pollen tube branching in the chalazal region of the ovule. Treub demonstrated that some tubes formed short branches even during their course between the bridge and the

[3] According to Treub, this figure merely represents the pollen tube lying below the embryo sac, which overlaps it. But Coulter and Chamberlain (1903, p. 149) contend that the pollen tube is lying within the embryo sac. See Treub's figures on plate 27, figures 1 *a–h*, which clearly convey his version.

[4] The italics in this paragraph are mine.

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chalazal region and also in the nucellus. In the present investigation it is seen that in *C. equisetifolia,* the pollen tube may branch even in the stigma. In *C. montana,* one tube was observed which had coiled around an embryo sac and formed a tuft of short branchlets.

(8) *Fertilization.*—Treub's account may be summarized as follows:

a. Besides the egg, the mature embryo sac contains as many as 50 endosperm nuclei before fertilization.

b. The pollen tube implants itself on the membrane of the embryo sac at a point far away from the place of attachment of the egg apparatus.

c. A male nucleus penetrates the membrane of the pollen tube and that of the embryo sac at the point of mutual contact, enters the embryo sac, and traverses the greater part of the sac and ultimately fuses with the egg nucleus after entering the egg cell from below.

Frye's account for *C. stricta* showed, however, that the mode of fertilization is quite similar in most ways to that described for other angiosperms. The present investigation fully confirms this. Briefly, the mature embryo sac is eight-nucleate and does not have any endosperm nuclei at the time of fertilization; the tip of the pollen tube pierces the embryo sac membrane at the point of situation of the egg apparatus; of the two sperms discharged by the tube, one fuses with the nucleus of the egg and the other with the two polar nuclei; triple fusion and the subsequent divisions of the primary endosperm nucleus commence before syngamy is completed; and the zygote divides only after wall formation starts in the endosperm. It seems certain (see also Frye, 1903) that Treub mistook a fertilized embryo sac for an unfertilized one and a discharged pollen tube for one that had not yet opened. Further, the single nucleus which Treub occasionally saw in the pollen tube was probably the undischarged and degenerating vegetative nucleus.

(9) *Endosperm and embryo.*—The observations made in the present study that originally the endosperm is nuclear and that cell formation proceeds from the micropylar end towards the chalaza are in agreement with Treub's findings. Some additional points noted by me are that the endosperm completely replaces the nucellus and that the embryo consumes all of this tissue.

In *C. equisetifolia* the first wall laid down in the zygote is transverse. By another transverse division of the basal cell, a row of three cells is organized. The micropylar cell and its nucleus enlarge but do not divide further; the middle cell forms a suspensor of four to six cells and the terminal one develops into the embryo proper. This roughly corresponds to Schnarf's (1929) "cruciferous type" or to one of its variants.

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A Brief Resume of Chalazogamy

In drawing comparisons between the Casuarinaceae and other chalazogams, one naturally turns to the so-called Amentiferae, a group which is generally considered to comprise the following families: Betulaceae, Fagaceae, Juglandaceae, Corylaceae, Myricaceae, Salicaceae, Leitneriaceae, Balanopsidaceae, and Garryaceae.[5] Of these, only Betulaceae (*Betula, Alnus*), Corylaceae (*Corylus, carpinus, Ostrya*) and Juglandaceae (*Juglans, Carya, Pterocarya*) are known to exhibit chalazogamy (see table 1).

TABLE 1

Families and species	Type of chalazogamy	Author and reference
1. BETULACEAE		
Betula alba	Extravesicular chalazogamy	Nawaschin, 1894
B. pendula ?	Extravesicular chalazogamy	Nawaschin, 1894
Alnus glutinosa	Extravesicular chalazogamy	Nawaschin, 1894
A. viridis	Extravesicular chalazogamy	Nawaschin, 1899
2. CORYLACEAE		
Corylus avellana	Intravesicular chalazogamy	Benson, 1894 Benson et al., 1906 Nawaschin, 1895 Nawaschin, 1899 a
Carpinus betulus	Intravesicular chalazogamy	Benson, 1894 Benson et al., 1906
Ostrya carpinifolia	Not ascertained	Finn, 1936
3. JUGLANDACEAE		
Juglans cinerea	Extravesicular chalazogamy	Nawaschin, 1895 a
J. regia	Extravesicular chalazogamy	Nawaschin, 1895 a Nast, 1941 Nawaschin & Finn, 1913
J. nigra	Extravesicular chalazogamy	Nawaschin & Finn, 1913
Carya olivaeformis	Not ascertained	Billings, 1903
C. pecan	Not ascertained	Woodroof & Woodroof, 1927
C. alba	Not ascertained	Karsten, 1902
C. cordifolia	Not ascertained	Karsten, 1902
Pterocarya Fraxinifolia	Not ascertained	Karsten, 1902
4. CASUARINACEAE		
Casuarina suberosa	Extravesicular chalazogamy	Treub, 1891
C. glauca	Extravesicular chalazogamy	Treub, 1891
C. Rumphiana	Extravesicular chalazogamy	Treub, 1891
C. stricta	Not ascertained, but extravesicular chalazogamy is most probable	Frye, 1903
C. equisetifolia	Extravesicular chalazogamy	(Present study)
C. montana	Extravesicular chalazogamy	(Present study)

[5] A suggestion has been made (see Hallock, 1930) that the Garryaceae should be removed from this group and placed among the Umbelliflorae.

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(1) *Types of chalazogamy.*—In the Betulaceae, Juglandaceae, and Casuarinaceae, the pollen tube enters the nucellus through the intercellular spaces and reaches the top of the embryo sac; from there it bends down and applies itself against the membrane of the embryo sac near the egg apparatus in the same way as if it had entered through the micropyle (figs. 37, 38). On the other hand, in the Corylaceae, according to Benson (1894), the pollen tube comes in contact with the caecum of the embryo sac that is to be fertilized, pierces it and proceeds upwards through its cavity, discharging its contents just below the egg (see Benson, 1894, figs. 50, 51; Benson et al. 1906, fig. 1).

For the first type, which occurs in the families Betulaceae, Juglandaceae, and Casuarinaceae, the name "extravesicular chalazogamy" may be applied, implying that the pollen tube reaches the egg by travelling outside the embryo sac that is to be fertilized. For the second type, which is reported in the Corylaceae, the term, "intravesicular chalazogamy" may be used, from the fact that here the pollen tube reaches the egg by a direct penetration of the embryo sac at its chalazal end.

(2) *Branching of the pollen tube.*—Table 2 presents a list of those plants that are characterized by having branching pollen tubes. It may be noted from a comparison of tables 1 and 2 that branching tubes occur in almost all chalazogamous species.

TABLE 2

Plant	Author	*Remarks*
Fagus sp. *Quercus* sp. *Betula alba* *Carpinus betulus* *Corylus avellana*	Benson, 1894	Benson considers this to be a very general feature in the "Amentiferae." In *Quercus*, the pollen tubes form short branches at their tip.
Betula alba	Nawaschin, 1894	After reaching the apex of the embryo sac, the tip of the pollen tube gives rise to short protuberances.
Juglans regia	Nawaschin, 1895 a	The pollen tubes profusely branch throughout their course.
Juglans nigra	Nawaschin & Finn, 1913	
Carya olivaeformis	Billings, 1903	As in *Juglans*.
Ulmus americana	Nawaschin, 1898	As in *Juglans*.
Cannabina sativa	Zinger, 1898	The tube gives rise to short branches at its tip.
Pothos longifolia	Hofmeister, 1859	The tube proliferates into short branches.
Hippeastrum aulicum		
Casuarina species	Treub, 1891 Frye, 1903 (Present study)	Branching invariably occurs at the chalazal region of the ovule; occasionally also in the stigma and in the nucellus.

(3) *Hibernation.*—The period between pollination and fertilization is usually a long one in the chalazogams. In most genera, the ovules

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do not have even the archesporial tissue differentiated at the time of pollination. This has led some writers (e. g. Baillon, cited by Benson, 1894) to think that here the pollen tube undergoes a period of rest in an encysted form and that it may even pass into a "secondary pollen grain" stage. Benson was, however, unable to obtain any evidence for the existence of such a condition.

I made a special effort to study this point in *C. equisetifolia*. Collections were made on every third day after pollination and the pistils were examined both with the help of suitably cleared whole mounts as well as serial sections. No pollen tube showed evidence either of cyst formation or of any other similar adaptation for undergoing a period of rest. In this connection the following data speak for themselves.

a. The pollen grains germinate on the stigma within three days after pollination. At this stage, the ovules are still very young and only beginning to grow. b. About six days later, when the pollen tube is crossing the bridge, the nucellus shows a differentiation of sporogenous and parietal layers. c. Twelve days later, when the pollen tube has already reached the chalaza, the embryo sacs are still at the two- or four-nucleate stages. d. Twenty days after the preceding stage, the pollen tube begins to branch in the chalaza and mature embryo sacs are seen towards the upper part of the nucellus. e. Fertilization occurs from about nine to twelve days after the stage d. The duration between pollination and fertilization is therefore, about 45–50 days and the development of the pollen tube continues without any break for the entire period.

(4) *Other sporogamous methods of the pollen tube.*—True chalazogamy—in which the pollen tube enters the ovule through the chalaza and reaches the micropylar end of the embryo sac by an upward movement in the nucellus—has till now been reported only in the Casuarinaceae, Corylaceae, Juglandaceae, and Betulaceae. Other aporogamous modes of the pollen tube behavior are also known, however. Generally in such plants (*Ulmus*, Nawaschin, 1898; *Cannabis*, Zinger, 1898; *Cucurbita*, Longo, 1901; *Alchemilla*, Murbeck, 1901) the pollen tube bores through the integuments at some phase of its course in order to enter the nucellus; moreover, the final entry will be invariably from a place nearer to the micropyle. It may also be noted that such abnormal behavior is not constant in any of the species and is variable even in the different ovules. On the other hand, in all the chalazogamous plants, the pollen tubes invariably pass from the chalaza to the egg apparatus through the nucellus (Casuarinaceae, Betulaceae, Juglandaceae) or through the very embryo sac that is to be fertilized (Corylaceae).

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(5) *Terminology.*—Some authors (e. g. Rendle, 1938) consider the aporogamous behavior of the pollen tube also as a kind of chalazogamy. This view does not seem to be correct. Wettstein (1924), Porsch (1907), Nawaschin & Finn (1913) and others have already distinguished true chalazogamy from aporogamy. Pirotta & Longo (1900) proposed the term "acrogamy" for the entrance of the pollen tube through the micropyle; "basigamy" for its entrance through the chalaza; and "mesogamy" for its entrance by intermediate routes. In the opinion of the present student, the term "chalazogamy" should be retained in place of "basigamy" on the principle of priority. "Porogamy" which denotes the entrance of the pollen tube through the micropyle has been in use for a very long time and there is no need to replace it by a new term, "acrogamy." The term "mesogamy" is suitable for all cases of an intermediate nature.

Summary

Two species of *Casuarina, C. equisetifolia* and *C. montana,* are studied from the point of view of embryology.

In the microsporangium the primary parietal layer gives rise to the endothecium, middle layers, and tapetum, and the primary sporogenous layer to the microspore mother cells. The latter undergo simultaneous divisions to form microspore tetrads. The pollen grains are two-celled at the time of shedding.

The ovary is made up of two locules of which one is sterile and the other bears two ovules. The ovules originate from the placenta in a lateral manner but later become epitropous, with the micropyle pointing towards the style. The chalazal conducting strand continues upwards into the nucellus. Some of the centrally situated sporogenous cells also seem to elongate and contribute towards the extension of the strand in the nucellus.

The primary sporogenous cells in the nucellus divide mitotically to produce an increased number of megaspore mother cells during the same time as the primary parietal layer is giving rise to the parietal tissue.

The female gametophyte is of the monosporic eight-nucleate type. More than one megaspore of a tetrad germinates further so that as many as 20–25 embryo sacs are present in the same nucellus. The embryo sac develops a tubular chalazal caecum; the antipodals are ephemeral.

The pollen tube enters the chalaza and undergoes some branching. The particular branch carrying the gametes makes its way between the swollen vesicles of the embryo sac caeca and eventually reaches the

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top of an embryo sac. Entry into the embryo sac is effected at a point close to the egg apparatus.

Early divisions of the endosperm are free nuclear. Wall formation commences from the micropylar end, while free nuclear divisions still continue at the antipodal end.

The embryo development roughly corresponds to the "cruciferous type." Occasionally polyembryony occurs, which may be due to the entry of more than one pollen tube followed by a fertilization of two or more embryo sacs in the same nucellus.

A brief survey of chalazogamous plants with reference to pollen tube behavior is presented. Certain terminologies connected with chalazogamy are discussed.

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EXPLANATION TO FIGURES

PLATE I. *Casuarina equisetifolia*

Fig. 1. Side view of the male flower; the outer perianth towards the side of the onlooker is partly trimmed off, × 40.

Fig. 2. Side view of the same, from the adjacent side, × 40.

Fig. 3. Floral diagram of the male flower.

Fig. 4. Median longitudinal section of a young male flower, × 60.

Fig. 5. L. s. of a portion of a female strobilus showing the position of the woody valves and ovaries, × 10.

Fig. 6. A single female flower, × 10.

Fig. 7. Floral diagram of the female flower.

Fig. 8. Ovary after pollination; note the shrivelled style and the development of the wing-like expansion of the ovary, × 5.

Fig. 9. L. s. of a very young ovary showing the position and topography of the ovules, × 40.

Fig. 10. Same as Fig. 9, but still older, at about the time of fertilization. Note the erect position of the ovules and the "bridge," × 40.

Fig. 11. Same as Fig. 10; Figs. 11a to 11h represent transverse sections of an ovary at different levels as marked in Fig. 11 by corresponding letters. 11c′ and 11c″ represent the longitudinal sections passing through the planes indicated by lines c′c′ and c″c″ in Fig. 11c, × 40.

PLATE II. *Casuarina equisetifolia*

Fig. 12. T. s. of a part of a young anther to show the archesporium; two locules are shown. In one of the locules the archesporial cells are resting, in the other, in division, × 450.

Figs. 13 and 14. Differentiation of the endothecium, wall layers and tapetum, × 450.

Fig. 15. A loculus of an anther showing the epidermis, endothecium, wall layers, tapetum, and microspore mother cells, × 450.

Fig. 16. Some of the cells of the endothecium to show the characteristic banded thickenings, × 300.

Fig. 17. Uninucleate microspore, × 300.

Fig. 18. Division of the nucleus of the microspore, × 300.

Fig. 19. Pollen grain showing the vegetative and generative cells, × 300.

Fig. 20. Pollen grain at the time of shedding, × 300.

Fig. 21. L. s. of young nucellus showing three hypodermal archesporial cells, × 450.

Fig. 22. Same as Fig. 21. Slightly later stage showing the increase in the sporogenous as well as in the parietal tissue, × 450.

Fig. 23. L. s. of an entire ovule at the time of commencement of the meiotic divisions in the megaspore mother cells. Note the conducting strand extending into the core of the sporogenous cells, × 200.

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Fig. 24. Division of megaspore mother cell and the formation of dyad cells, × 450.

Fig. 25. Division of the dyad cells leading to the formation of the tetrad of megaspores, × 450.

Fig. 26. A portion of the sporogenous tissue showing tetrads of megaspores, some degenerating and others germinating to various stages; note the commencement of the embryo sac caecum in the two-nucleate embryo sac, × 450.

Fig. 27. Two linear tetrads in which all the megaspores have developed into eight-nucleate embryo sacs; many of them are showing indications of internal organization, × 450.

Fig. 28. Division of the nuclei of the two-nucleate sac, × 450.

Fig. 29. Division of the nuclei of the four-nucleate sac, × 450.

Fig. 30. Unorganized eight-nucleate embryo sac, × 450.

Fig. 31. A typical eight-nucleate embryo sac at maturity, × 400.

Fig. 32. Ovule at the time of fertilization; note the embryo sac caeca, whose terminal swllings are lying in contact with the vascular conducting strand, × 60.

Figs. 33–35. Variations in the structure of the egg apparatus; explanation in text, × 450.

Plate III. *Casuarina equisetifolia*

Fig. 36. Germination of pollen grains on the stigma, × 60.

Fig. 37. Optical longitudinal section of an entire ovary to show the general topography of the internal organs and the course of the pollen tube, × 20.

Fig. 38. L. s. of an ovary reconstructed from six serial sections, to show the course of the pollen tube in the ovule, × 80.

Fig. 39. Double fertilization, × 300.

Fig. 40. Tip of a pollen tube which was on its way to an embryo sac in the nucellus; note the sheathed condition of the sperms, × 450.

Fig. 41. Embryo sac after fertilization showing the zygote and eight endosperm nuclei in division, × 100.

Fig. 42. An early stage in the formation of endosperm; note the peripheral arrangement of the nuclei, × 100.

Fig. 43. Embryo sac showing two-celled embryo; the endosperm is becoming cellular in the micropylar region and free nuclear divisions are still taking place in the chalazal region. Note the persistence of spindles in the lower half, × 60.

Plate IV. *Casuarina equisetifolia*

Fig. 44. Portion of endosperm showing the three-celled proembryo, × 200.

Fig. 45. Embryo showing the haustorial cell, four suspensor cells and the longitudinally divided terminal cell. Note the divisions in the endosperm cells, × 140.

Fig. 46–48. Further stages in the development of the embryo (Fig. 48 is a drawing of a whole mount preparation of a dissected embryo), Figs. 46, 47, × 315; Fig. 48, × 275.

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Fig. 49. Later stage of the embryo, in which the cotyledons have differentiated; a few of the nucellar cells are still visible below the micropyle, × 30.

Fig. 50. L. s. of a late embryo showing cotyledons, radicle, and the stem tip, × 40.

Fig. 51. An embryo (surface view of a cotyledon) at the stage of dispersal, × 30.

Fig. 52. Ovule with double nucelli, × 400.

Fig. 53. Two two-celled proembryos surrounded by endosperm cells, × 450.

Fig. 54. A sexually produced embryo and a multinucleate nucellar cell which perhaps develops into an adventive embryo, × 275.

PLATE V. *Casuarina equisetifolia*

Fig. 55. L. s. of a fruit at the time of the octant stage of the embryo, × 20. *a*. Stylar tissue; *b*. Pad of spirally thickened cells; *c*. Crystalliferous tissue; *d*. Outer integument; *e*. embryo; *f*. Nucellus; *g*. Endosperm; *h*. inner wall of the ovary; *i*. Ovular stalk.

Fig. 55a. T. s. at the region dotted in Fig. 55, × 20.

Fig. 56. Crystalliferous cells from the region *c* in Fig. 55, showing ramified pits and the solitary crystal in each cell, × 450.

Fig. 57. Spirally thickened cells from region *b* in Fig. 55, × 100.

Fig. 58. A metaphase plate from a cell of the root tip, showing 18 chromosomes, × 900.

Fig. 59. Ovule in which three pollen tubes have entered the nucellus and their tips are entangled over an embryo sac, × 200.

Fig. 59a. Tangled portion of the pollen tubes enlarged from Fig. 59, × 300.

Fig. 60. Ovule in which one pollen tube has fertilized an embryo sac and a second pollen tube is lying on the apex of another embryo sac, × 200.

Fig. 61. Ovule in which two pollen tubes have fertilized two embryo sacs, × 200.

Fig. 62. Ovule with abnormal placenta, × 40.

Fig. 62a. Cells from the abnormal placenta showing pits (enlarged from fig. 62), × 450.

PLATE VI. *Casuarina montana*

Fig. 63. L. s. of a young ovary showing the horizontal position of young ovules, × 20.

Fig. 64. The same, later stage showing the epitropous position of the ovule, × 20.

Fig. 65. Young nucellus, just after the formation of the parietal layers; note the sporogenous cells still dividing towards the lower end, × 275.

Fig. 66. A later stage of the nucellus showing the germination of the megaspores, the procambial strand in the nucellus and the divisions of the sporogenous cells still going on towards the basal end, × 275.

Fig. 67. Mature embryo sac showing the egg apparatus and secondary embryo sac nucleus; the antipodals are degenerating in this sac, × 450.

Fig. 68. Egg apparatus showing the egg cell and two synergids, × 450.

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PLATE VII. *Casuarina montana*

Fig. 69. L. s. of an ovule showing the entry of the pollen tube and its branching in the chalazal region, × 20.

Fig. 70. Branching portion of the pollen tube enlarged from Fig. 69 to show the sperms and the vegetative nucleus, × 100.

Fig. 71. A portion from Fig. 70 further enlarged to show the alignment of cells in the chalaza and the details of the sperms and vegetative nucleus, × 450.

Fig. 72. Sperms and the vegetative nucleus enlarged from the tip of the pollen tube in Fig. 74, × 450.

Fig. 73. Sperms and the vegetative nucleus enlarged from one of the branchlets of the pollen tube in Fig. 75, × 450.

Fig. 74. An abnormal behavior of the pollen tube, × 400.

Fig. 75. Another abnormal behavior of the pollen tube; explanation in text, × 100.

Fig. 76. A fertilized embryo sac showing the course of the pollen tube in the nucellus, zygote and four endosperm nuclei; the persisting synergid in this case is binucleate, × 300.

Fig. 77. A metaphase plate from a cell of the root tip, showing 18 chromosomes, × 900.

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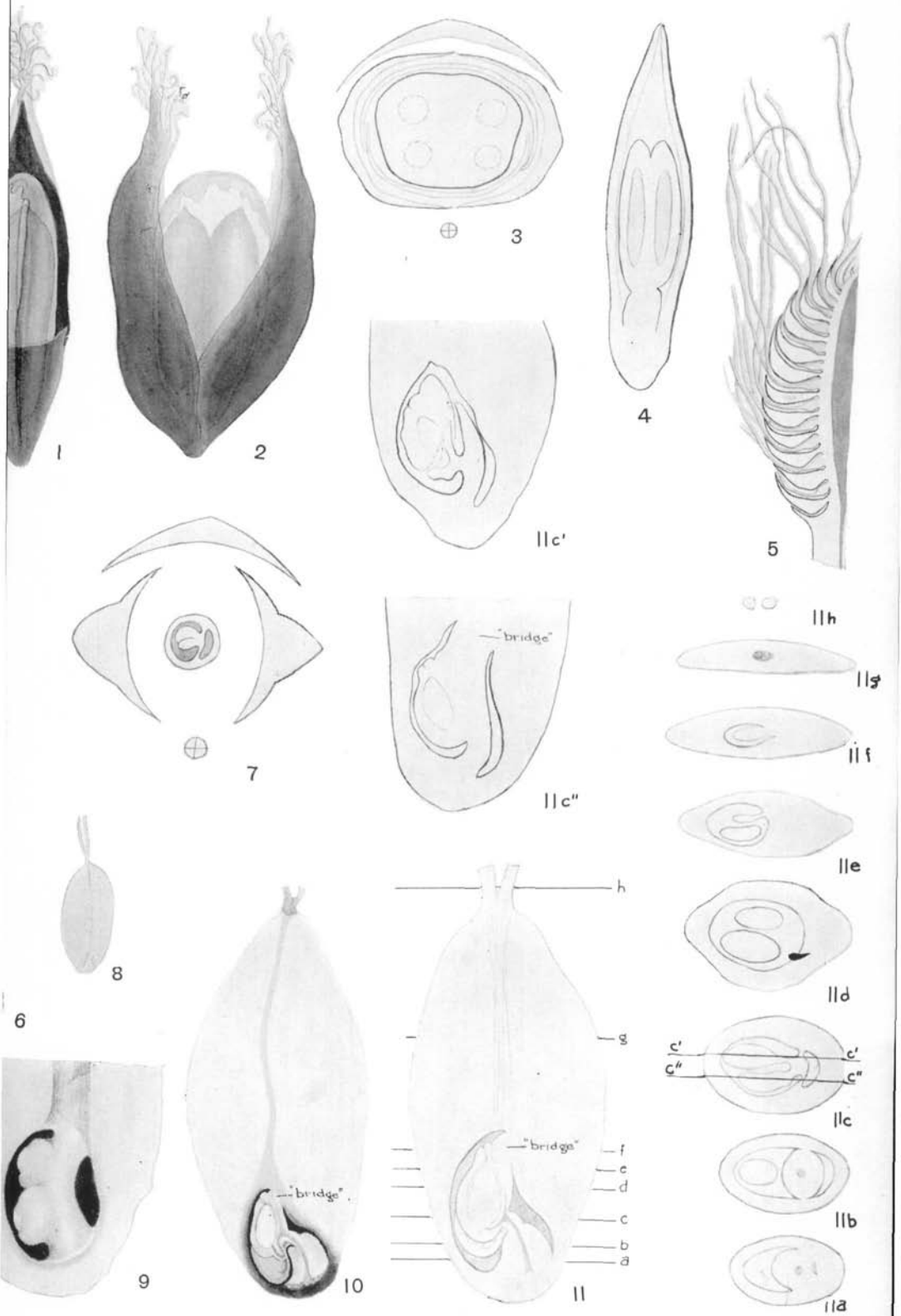

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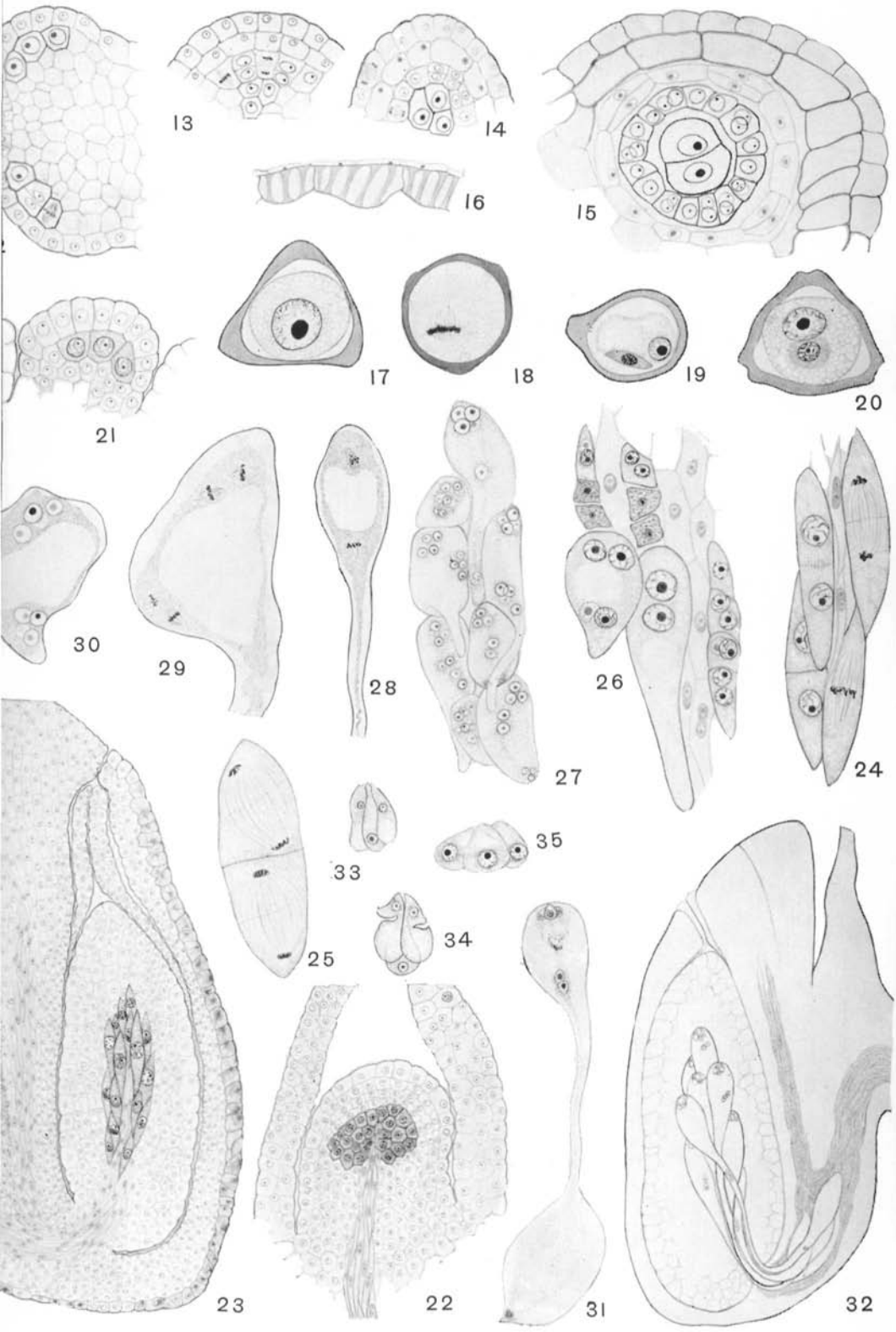

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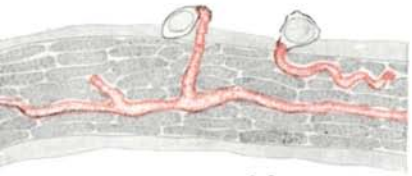

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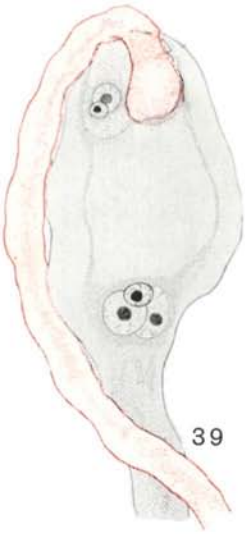

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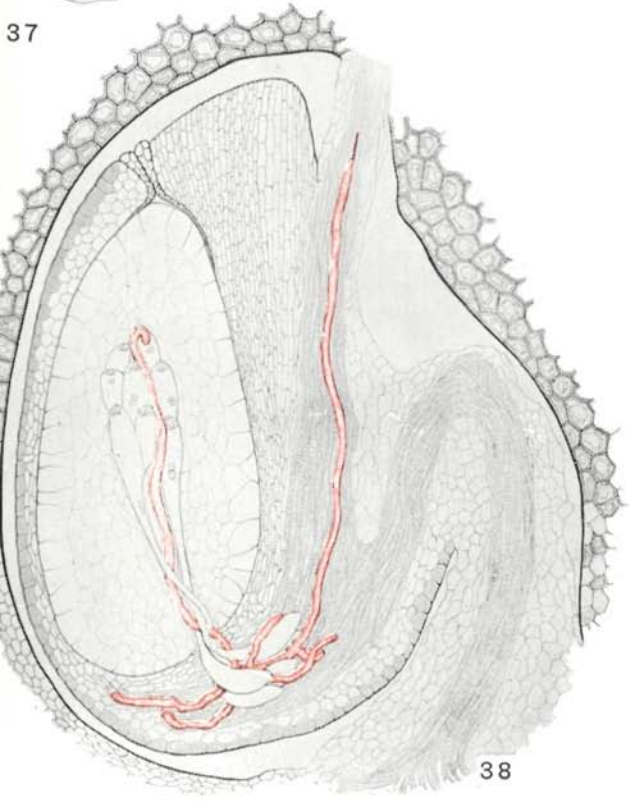

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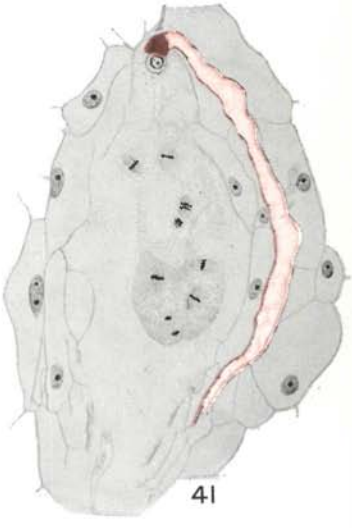

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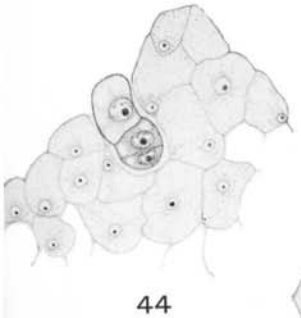

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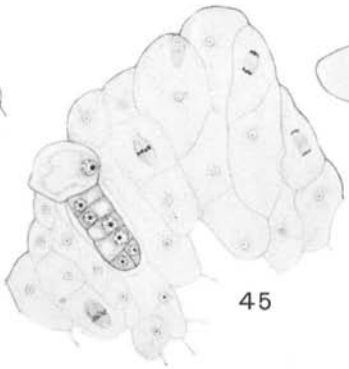

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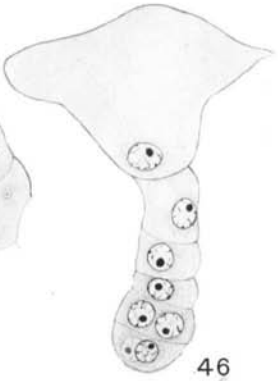

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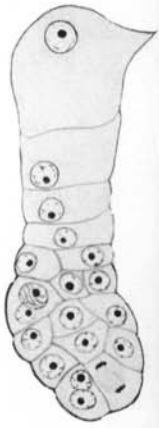

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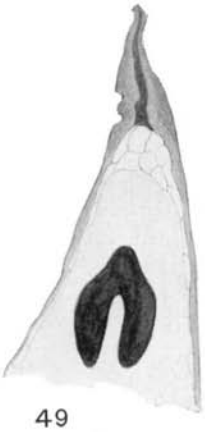

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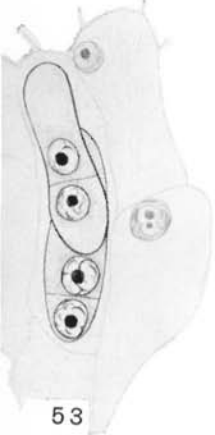

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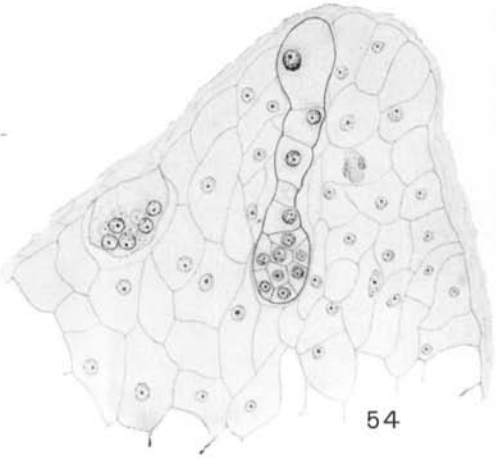

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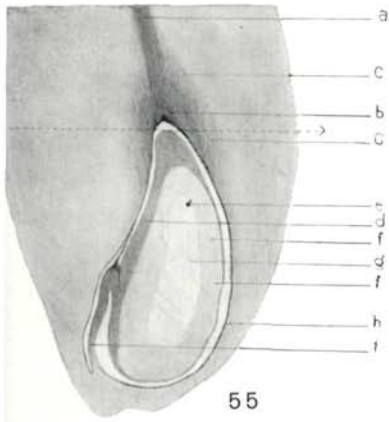

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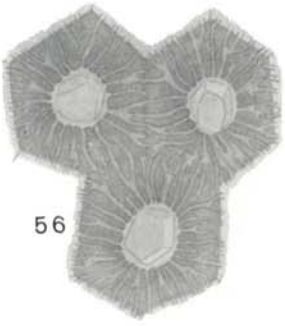

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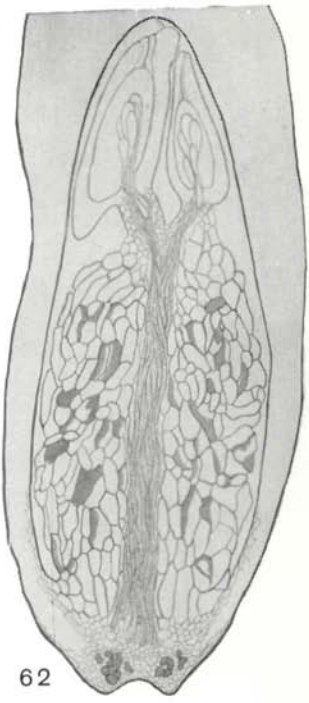

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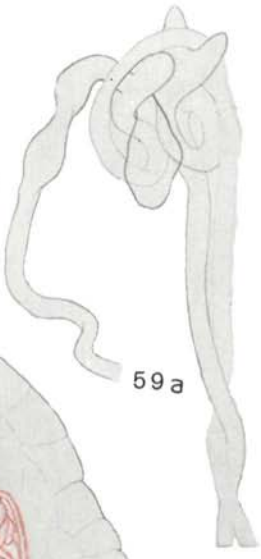

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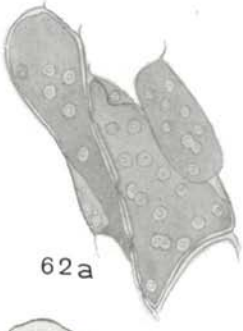

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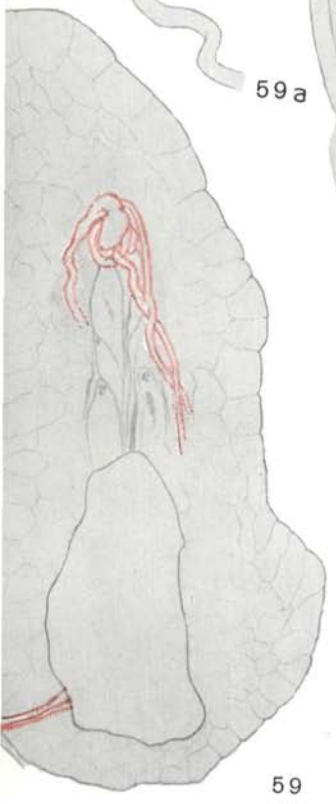

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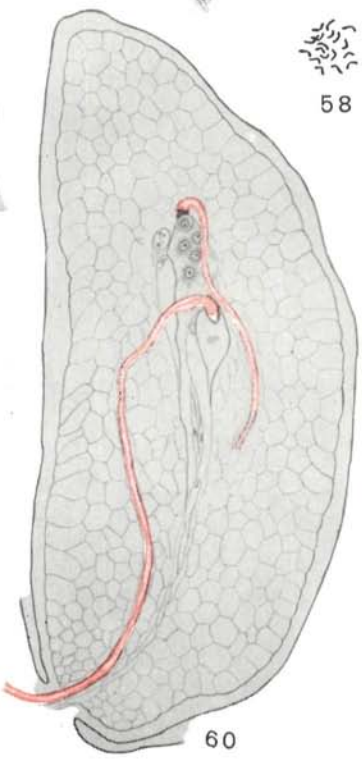

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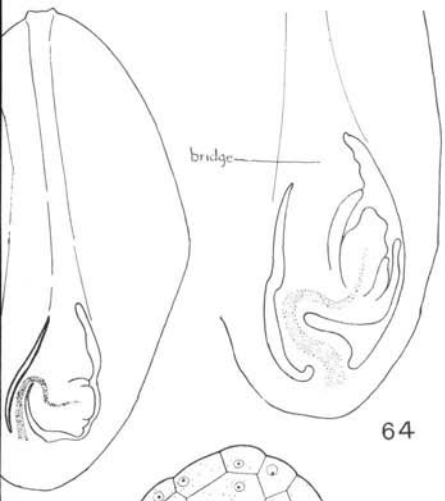

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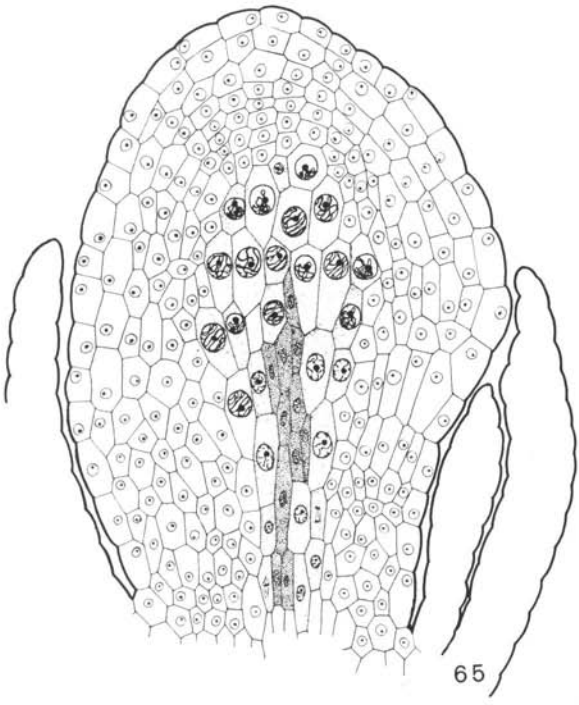

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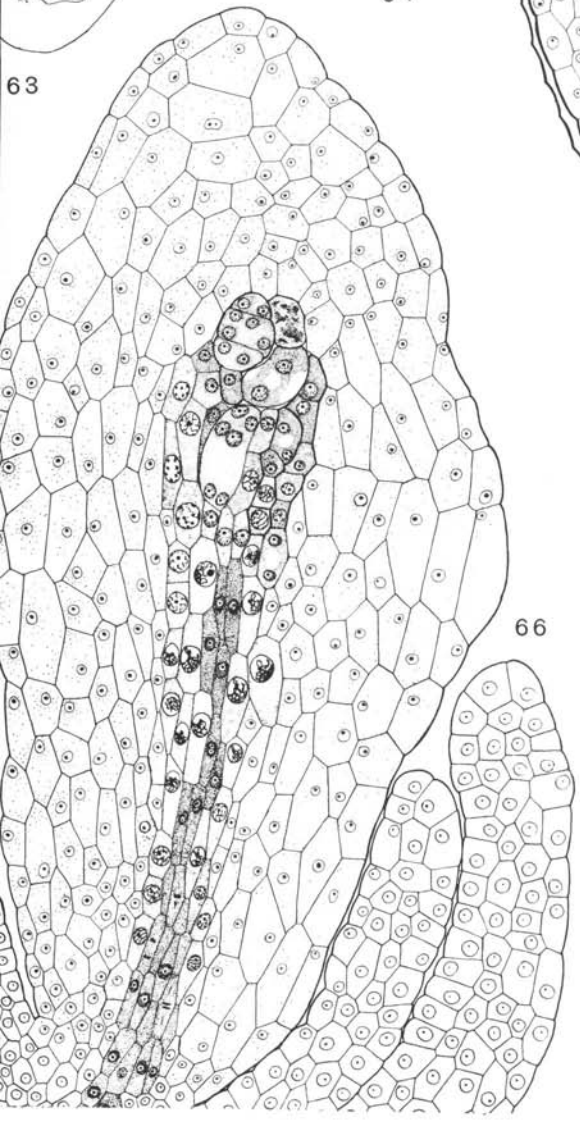

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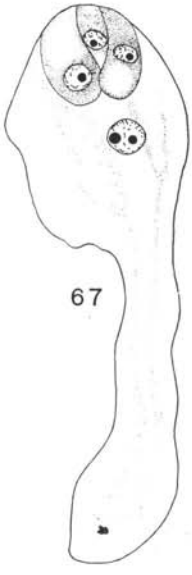

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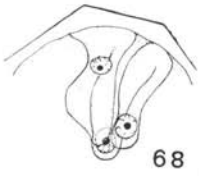

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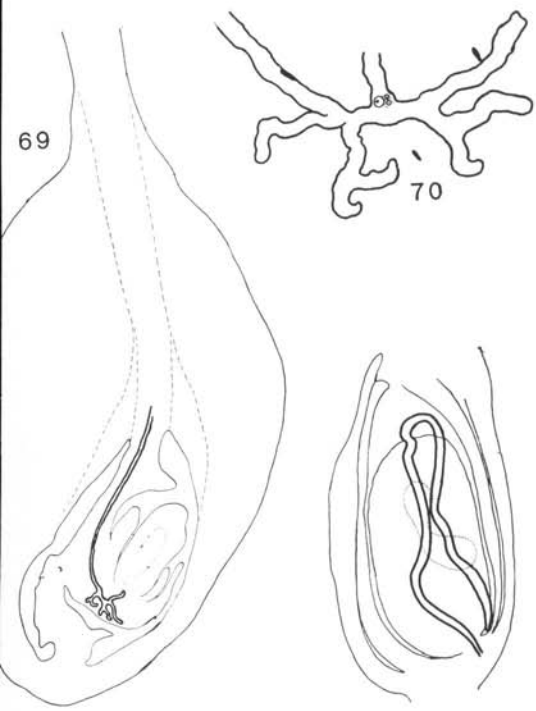

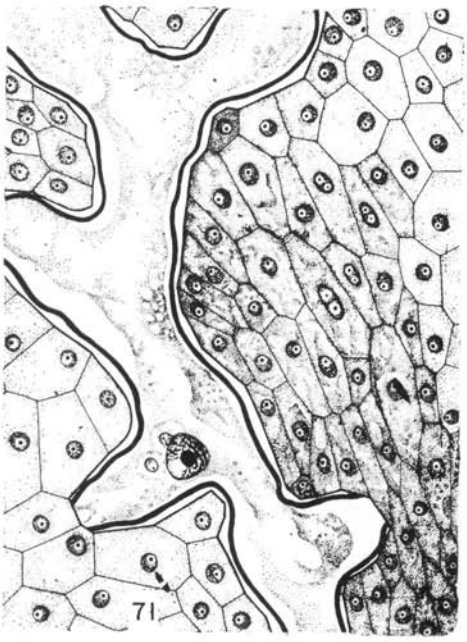

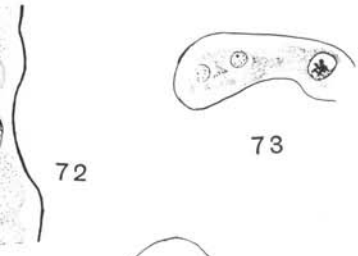

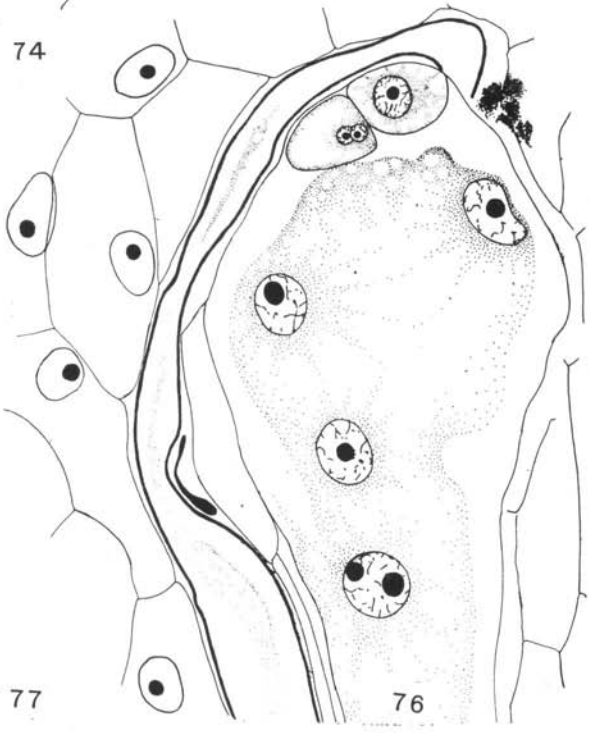

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CENTENNIALS, SESQUICENTENNIALS, AND BICENTENNIALS OF CHEMICAL INTEREST DURING 1949.

By Ernest H. Huntress

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CENTENNIALS, SESQUICENTENNIALS, AND BICENTENNIALS OF CHEMICAL INTEREST DURING 1949

ERNEST H. HUNTRESS

Massachusetts Institute of Technology

Received November 23, 1948.

The observance of holidays in secular and religious calendars was originally devoted to the remembrance of notable events, circumstances or persons. Science in general and chemistry in particular could profit by seizing appropriate opportunities to remind itself of progress. In the belief that alert students and teachers at all intellectual levels will appreciate a memorandum of special anniversaries falling within the coming year, the present brief treatment has been prepared as a corollary of a long-sustained interest[1,2] in the pedagogical utilization of scientific anniversaries.

Although the present paper is primarily concerned with the anniversaries of birth or death of chemists, the author has allowed himself to include a few representatives of other fields when the subject comprises a development or personality deserving better acquaintance by every broadly educated scientific student. The selected references are mainly restricted to the periodical literature, where a wealth of biographical material of superb character has frequently been ignored. Particular biographies or autobiographies in book form are readily found in library card catalogues and bibliographies; but biographica data included in commonly accessible scientific and technical periodicals seem to be difficult to locate when needed.

The brief memoranda comprising the text for each entry is intended to draw attention to only a few of the highlights of each subject's career and accomplishments. In the selected citations no attempt has been made to distinguish between biographies, jubilees, obituaries, memorials, or other characterizations, all being designated by "B". Portraits, however, are classified as P_1, P_2, P_2 in diminishing order of quality, the highest category being reserved for full-page pictures printed on only one side of the sheet and often on special paper.

[1] Huntress, "Daily Chemical Anniversaries as a Teaching Tool," J. Chem. Education *14*, 328–344 (1937).

[2] Huntress, "The 100th Anniversary of the Birth of F. K. Beilstein," J. Chem. Education *15*, 303–309 (1938).

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RED LETTER DAYS DURING 1949

Jan. 22.	Sesquicentenary of death of SAUSSURE
Jan. 26.	Sesquicentenary of birth of CLAPEYRON
Feb. 19.	Sesquicentenary of birth of REICH
Mar. 7.	Centenary of birth of HALLER
Mar. 23.	Centenary of death of DEL RIO
Mar. 24.	Centenary of death of DÖBEREINER
Mar. 28.	Bicentenary of birth of LAPLACE
Apr. 25.	Centenary of birth of KLEIN
Apr. 27.	Centenary of birth of HILL
May 17.	Bicentenary of birth of JENNER
May 24	Centenary of birth of MUNROE
July 3.	Bicentenary of death of JONES
July 12.	Centenary of birth of OSLER
July 17.	Centenary of birth of REVERDIN
July 19	Centenary of birth of MELDOLA
Aug. 16.	Centenary of birth of KJELDAHL
Sept. 8.	Centenary of birth of HELL
Sept. 27.	Centenary of birth of PAVLOV
Oct. 18.	Sesquicentenary of birth of SCHÖNBEIN
Nov. 3.	Bicentenary of birth of D. RUTHERFORD
Nov. 16.	Centenary of birth of E. S. DANA
Nov. 29.	Centenary of birth of J. A. FLEMING
Nov. 29.	Centenary of birth of G. WAGNER
Dec. 6.	Bicentenary of death of BLACK

SAUSSURE, HORACE BENEDICT DE

Born Feb. 17, 1740, at Conches, an estate on the Arve River near Geneva, Switzerland; died Jan. 22, 1799, at Geneva, age 59.

This Swiss scientist was primarily geologist and mountain climber, but also botanist, physicist and meteorologist. At age 22 he became professor of philosophy at the Academy (now University) of Geneva where he remained 24 years (1762–1786). His early interest in botany led him to undertake many journeys in the Alps which later served as his geological laboratory. Among his more famous ascents were those of Mount Blanc (1787), Col du Géant (1788), Crammont (1784, 1788), St. Theodule Pass to Zermat (1789), Klein Matterhorn (1792). The description of seven of his Alpine journeys was published as "Voyages dans les Alpes" (4 vols. 1779–96; 8 vols. 1780–96).

Saussure, who is not to be confused with his son Nicolas Theodor de Saussure (1767–1845), was first (1762) to distinguish between epidermis and cortex of plants. He was first to adopt (1779) the term

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"geology," whose content had been construed earlier first as part of mineralogy, then of physical geography.

In the meteorological aspects of his work Saussure found ample opportunity to display his inventive talents. He devised (1790) a cyanometer to measure the blue color of the sky and a diaphanometer to indicate the relative transparency of the air. In 1783 he published the famous "Essais sur l'Hygrometrie" [No. 115 (1900) of Ostwald's Klassiker der Exakten Wissenschaften] which is still a model of scientific experiment and reasoning. Here he described the hair hygrometer in which the change in length of a human hair with variations in humidity was caused to move a needle on a dial. Saussure devoted great care to the selection of hairs, to freeing them from grease, and to an exhaustive study of their performance. Although for a century other methods of humidity measurement were favored, the introduction of self-recording instruments has led to renewed use of the hair type. The latest application of his method is in the little meteorographs attached to weather balloons used for determination of meteorological data at high altitudes.

Saussure became (1788) a foreign member of the Royal Society of London, his election occurring at the same meeting as that of Lavoisier.

A "Life of Horace Benedict de Saussure" by D. W. Freshfield was published in 1920 by E. Arnold Co. of London.

Clapeyron, Benoît-Paul-Émile

Born Jan. 26, 1799, at Paris, France; died Jan. 28, 1864, at Paris.

French engineer. Some unresolved doubt exists regarding date of birth (some sources giving Feb. 21, or Feb. 26), but all agree on year as 1799. Clapeyron was student at l'Ecole Polytechnique at Paris. After some practical construction experience including a period in Russia, he became professor of mechanics at l'Ecole de Ponts et Chaussées, Paris.

In 1834 he published in the Journal d'Ecole Polytechnique a classical memoir, "Sur la puissance motrice de la chaleur," which also appeared later in a more generally accessible journal [Ann. Physik. *59*, 446–451; 566–586 (1843)]. He put into analytical form the argument for the extent to which heat can be converted into work (in the case of a perfect gas) first advanced by N. L. S. Carnot. This taken together with application of the first law of thermodynamics (discovered in 1842) enabled Clausius and Lord Kelvin to deduce the theorem now generally known as the second law of thermodynamics. Clapeyron's name is by chemists usually associated with the so-called

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Clapeyron equation for calculation of the change in boiling point of a liquid with change of pressure.

On March 22, 1858, Clapeyron was elected a member of the French Academy of Science, succeeding Cauchy, the French mathematician.

Biographical material on Clapeyron is extremely meager and no periodical references have been locatable.

REICH, FERDINAND

Born Feb. 19, 1799, at Bernburg, halfway between Halle and Magdeburg in Freistaat Anhalt, Germany; died April 27, 1882.

Reich commenced studies at Göttingen (1822) under Strohmeyer; the following year in Paris was spent at the Sorbonne, the School of Mines and the College of France. Subsequently, Reich was associated for more than 40 years with the Freiberg School of Mines, including appointments as professor of theoretical chemistry (1842–1856) and professor of physics (1827–1860).

In 1863, while seeking thallium in some zinc ores, Reich obtained a material which he recognized as the sulfide of a new element. Because of his own color-blindness Reich caused his assistant, Hieronymus T. Richter, to execute the necessary spectroscopic examination. Since the flame test showed a brilliant indigo line different from that of cesium, the new element was named indium [J. prakt. Chem. (1) *89*, 441–442 (1863); (1) *90*, 172–176 (1863); (1) *92*, 480–485 (1864)]. Subsequently the assistant attempted to give the impression [cf. J. Chem. Education *7*, 1085–1086 (1930)] that he, rather than Reich, had discovered the new element. Reich and Richter made preliminary studies of simple indium compounds and even obtained the free metal, but extensive studies were (at Reich's suggestion) made by his student Winkler.

P_3B J. Chem. Education *9*, 1429–1434 (1932).

HALLER, ALBIN

Born March 7, 1849, at Felleringen, near Mulhouse, Upper Alsace; died April 29, 1925.

After achieving doctorate (1879) Haller joined staff of the École Superieur de Pharmacie at University of Strassbourg. In 1885 he became professor on the faculty of sciences at University of Nancy. He succeeded (1899) Friedel as professor of organic chemistry at the Sorbonne, University of Paris, and upon the retirement of Lauth became also director of the Municipal School of Chemistry and Physics of the City of Paris, retaining this position until his death.

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Haller published more than 250 research papers on topics which included the chemistry of camphor and its relatives, phthaleins, anthrones, indanones, anthracene derivatives, pseudoacids, etc. He was first to demonstrate that camphor is a ketone, and that it contains the $-CH_2-CO$ group; he first prepared iodocamphor and cyanocamphor and achieved a partial synthesis of camphor itself which laid the basis for the later establishment by Bredt of its present formula. Haller was first to recognize and extensively elaborate the value of sodamide in organic synthesis [for surveys of use of alkali amides see Bergstrom and Fernelius, Chem. Revs. *12*, 43–179 (1933); *20*, 413–481 (1937)]. He was first to recognize that borneol and isoborneol are stereoisomerides and to discover and name alcoholysis [Compt. rend. *143*, 657–661 (1906); Bull. soc. chim. (4) *1*, 876 (1907)].

Haller became a member of the French Academy of Science in 1900 and its president in 1923. He served several times as president of the French Chemical Society. He received in 1917 the Davy Medal of the Royal Society of London of which he became a foreign member in 1921. He was an editor of the Ann. chim. phys. (1907–1914) and upon its separation into two individual journals served (1914–1925) with C. Moureu as editor of the Ann. chim.

P_1B Bull. soc. chim. (4) *39*, 1037–1092 (1926) (incl. bibliog.): B J. Chem. Soc. *1927*, 3174–3178: B Proc. Roy. Soc. (London) *118-A*, I–III (1928): B Nature *115*, 843–844 (1925): P_3B Rév. gen. colloides *3*, 176–178 (1925): BP J. pharm. Alsace Lorraine *52*, 108–110 (1925): B Ann. chim. (10) *4*, 5–8 (1925): B Bull. soc. chim. (4) *37*, 685–688 (1925): B Bull. sci. pharm. 32, 347–351 (1925): B Bull. soc. chim. ind. Mulhouse *91*, 317–319 (1925): Bull. soc. chim. Belg. *34*, 160 (1925): PB Parfums France, No. 30, 213–221 (1925).

Del Rio, Andres Manuel

Born Nov. 10, 1764, in Madrid, Spain; died March 23, 1849.

After a bachelor's degree from the University of Alcalá de Henares, Del Rio was sent by his government to study at Paris under Darcet, at the Royal School of Mines in Freiberg, Saxony, under A. G. Werner, and at the Royal School of Mining and Forestry at Schemnitz, Hungary.

At age 30 he accepted an appointment at Mexico City and in 1795 began to teach at the School of Mines, just founded (1792) by Don Fausto de Elhuyar, a course in oryctognosy which included mineralogy, geognosy and paleontology, His first edition (1795) of "Elements of Oryctognosy" [reviewed in Ann. chim. (1) *21*, 221–224 (1797)] was regarded by von Humboldt (who had been his schoolmate at Freiberg)

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as the best mineralogical work which Spanish literature possessed at the time. Del Rio served about 50 years (1795–1849) as professor at the Mexico City School of Mines; in 1828, however, when most Spaniards were expelled from Mexico and despite his exception by the government, he voluntarily came to the United States and spent four years at Philadelphia.

In 1801 Del Rio discovered the element now known as vanadium. He first designated it as panchromium, then later as erythronium, but because its properties so closely resembled those described by Fourcroy for chromium, Del Rio became doubtful of the novelty of his material and published his work as, "The Discovery of Chromium in the Brown Lead of Zimapan." After the lapse of some 25 years, the Swedish chemist, Sefström, independently obtained (1830) from some Taberg iron a supposedly new element, noticed the beautiful colors displayed under certain circumstances by its solutions, and in allusion to Vanadis, the Scandinavian goddess of beauty, named it vanadium. Almost simultaneously Wöhler examined a sample of Del Rio's ore which had been brought to Europe by von Humboldt and found [(Poggendorf's) Ann. Physik *21*, 49 (1831)] that Sefström's vanadium was the element so long before designated by Del Rio as erythronium. An extensive study of vanadium compounds was concurrently made by Berzelius but it was not until June 16, 1869, that the isolation of metallic vanadium was announced by Sir Henry Roscoe.

P_3B J. Chem. Education *12*, 161–166 (1935); *11*, 413–419 (1934).

DÖBEREINER, JOHANN WOLFGANG.

Born Dec. 13, 1780, at Hof, Bavaria, Germany; died March 24, 1849, at Jena, Germany.

Although meagerly trained in science, Döbereiner developed great research ability and became (1810–1849) professor of chemistry, pharmacy and technology at the University of Jena. He was first (July 27, 1823) to observe that *at ordinary temperature* finely divided platinum was able to cause spontaneous ignition of hydrogen and oxygen as a result of which he developed a famous "Zündemaschine" (Döbereiner's lamp) or lighter [for history see Angew. Chem. *50*, 46–50 (1937); Chem. Ztg. *46*, 677–679 (1922); *57*, 2–3 (1933)].

In 1817 [(Gilbert's) Ann. Physik. *57*, 435–438 (1817)] and more fully in 1829 [(Poggendorf's) Ann. Physik. *15*, 301–307 (1829)] he called attention to the existence of *triads*, i. e., groups of three elements (e. g., chlorine, bromine, iodine; calcium, strontium, barium; lithium, sodium, potassium; sulfur, selenium, tellurium) in which the properties

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of that with intermediate atomic weight are also intermediate between those of the other two.

As the result of observation of an oily by-product obtained during the preparation of formic acid from carbohydrate material by the action of sulfuric acid and manganese dioxide, Döbereiner was the first [Ann. *3*, 141–146 (1832)] to obtain furfural. He was also the first to observe acetaldehyde-ammonia but this was fully characterized [Ann. *14*, 133–151 (1835); *22*, 273–277 (1837)] by Liebig. Döbereiner also made extensive studies on the oxidation of alcohol to acetic acid and is regarded [(Poggendorf's) Ann. Physik. *24*, 594–603 (1832)] as the real founder of rapid acetic acid manufacture.

P_3B J. Chem. Education 9, 1593–1594 (1932); B Z. Angew. Chem. *36*, 482–484 (1923).

LAPLACE, PIERRE-SIMON, MARQUIS DE

Born March 28, 1749, at Beaumont-en-Auge, in the Département Calvados of the Normandy district of France; died March 5, 1827, at Paris.

Laplace was a distinguished mathematician and astronomer. His systematic integration of the work of three generations of illustrious mathematicians in the monumental "Mécanique Célèste" (five volumes 1799–1825) is regarded as one of the greatest contributions to the development of science. The brilliant memoirs on the theory of probability led to his election as an associate (1773) and later as a full member (1785) of the French Academy of Sciences. His complete works were eventually republished by the French government (seven volumes 1843–1847) with a second edition in 1912.

KLEIN, CHRISTIAN FELIX

Born April 25, 1849, at Düsseldorf, Germany; died June 22, 1925, at Göttingen, age 76.

Klein was a mathematician, especially concerned with its application to physics, and regarded as one of the greatest and most influential of modern times. At age 17 he became assistant to J. Plücker at Bonn, later student of Clebsch at Göttingen, and Kummer at Berlin. He became (1872–1875) professor of mathematics at University of Erlangen and later occupied similar chairs at Munich Technische Hochschule (1875–1880), University of Leipzig (1880–1886) and finally Göttingen (1886–1913). He founded *Enzyklopädie der Mathmatischen Wissenschaften* (1895) and long (1872–1925) served as editor of the *Mathematische Annalen* founded (1868) by Carl Neumann [Math. Ann. *96*, 1–25 (1927)].

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His mathematical researches were chiefly concerned with geometry and theory of functions; his numerous books included a monumental treatise (1897–1910) with A. Sommerfeld on the theory of the top, and a brief autobiography. He traveled widely, lecturing many times in England and on two trips to America, where (1893) he represented Göttingen at the Columbian Exposition in Chicago. In 1908 he served as president of an International Commission on the Teaching of Mathematics.

P_1B Proc. Roy. Soc. (London) *A–121*, I–XIX (1928): P_1B Jahresber. Deut. Math. Ver. *27*, 217–228 (1918); *34*, 89, 197–213 (1925): P_1B Naturwissenschaften *7*, 275–317 (1919) (incl. bibliog.); B ibid. *13*, 765–772 (1925); B ibid. *14*, 1042–1043 (1926): P_1B Z. tech. Phyzik *7*, 2–7 (1926): P_3B Z. Ver. deut. Ing. *69*, 1118–1119 (1925): B Z. angew. Math. u. Mech. *4*, 86–92 (1924); *5*, 358–359 (1925): B Proc. Nat. Acad. Sci. U. S. *13*, 611–613 (1927): B Nature *116*, 475–476 (1925). B London Math. Soc. *1*, 25–32 (1926).

Hill, Henry Barker

Born Apr. 27, 1849, at Waltham, Mass.; died April 6, 1903.

Son of Rev. Thomas H. Hill (president of Harvard University, 1862–1868), H. B. Hill graduated from Harvard (1869), then spent next year in Berlin studying under A. W. Hofmann. On returning he was connected with the Harvard staff of chemistry for thirty-three years, successively as assistant (1870–1874), assistant professor (1874–1894), professor and director of the laboratory (1894–1903). In 1891–1892 he also taught organic chemistry at Mass. Inst. of Technology. Among his students who subsequently became notable were A. M. Comey, W. J. Hale, W. L. Jennings, C. F. Maberry, G. Oenslager, H. A. Torrey, and others.

His first two papers described a method of attack on the structure of uric acid subsequently employed by Emil Fischer with conspicuous success. However, in the course of his service for some years as consultant for the Carter's Ink Co. of Cambridge, Mass., Hill was led to study some by-products of the manufacture of acetic acid by distillation of wood. His recognition of furfural in this material led to more than 30 papers on furan chemistry, mainly published in the Proceedings of the American Academy of Arts and Sciences and in the American Chemical Journal. This work included a full study of mucobromic and mucochloric acids and establishment of their structures. This led to the discovery of nitromalondialdehyde and to a long line of ingenious syntheses of products derived from its reaction with other materials.

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P$_1$B Biog. Memoirs Natl. Acad. Sci. *5*, 255–266 (1905) (incl. bibliog.): B Am. Chem. J. *30*, 80–82 (1903): B J. Am. Chem. Soc. *25*, Proceedings A. C. S., 97–98 (1903): B Science *17*, 841–843 (1903): B Ber. *36*, 4573–4581 (1903) (incl. bibliog.): B Dict. Am. Biog. *9*, 33–34 (1932).

JENNER, EDWARD

Born May 17, 1749, at Berkeley, Gloucestershire, England; died Jan. 26, 1823, at Berkeley.

Jenner is regarded as the true discoverer of vaccination against smallpox. He was a physician and pupil of John Hunter in London. His investigations began about 1776 from the observation that persons who previously had cowpox were not susceptible to smallpox. Following a specific opportunity in 1796 to demonstrate the validity of this theory, he published (1798) a short treatise which led Cline, surgeon at St. Thomas' Hospital, to introduce vaccination at that institution, following which it was rapidly adopted in the army and navy and presently throughout the civilized world. Many honors were given to Jenner, including grants totalling 30,000 pounds from the British Government. Numerous book biographies of Jenner are available.

He is buried in the chancel of the parish church at Berkeley.

MUNROE, CHARLES EDWARD

Born May 24, 1849, at East Cambridge, Mass.; died Dec. 7, 1938, at Forest Glen, Maryland, in his ninetieth year.

He received S.B. (1871) from Lawrence Scientific School of Harvard University, where for next three years he assisted Profs. O. W. Gibbs and J. P. Cooke, and where the later distinguished F. W. Clarke, H. B. Hill, C. L. Jackson, and H. W. Wiley were among his close friends. During this period he established (1872) the first Harvard course in chemical technology, and the first (1873) summer school of chemistry in the United States. For the next dodecade (1874–1886) he was professor of chemistry at the U. S. Naval Academy at Annapolis, Md., leaving only for research (1886–1892) at the U. S. Naval Torpedo Station and War College at Newport, Rhode Island. His next move was to chair of chemistry at Columbian College (now George Washington University) at Washington, D. C., where he was dean of the Corcoran Scientific School (1892–1898) and of the School of Graduate Studies (1892–1917). During his 46 years in Washington, Munroe was also consultant on explosives in many government connections and was chief explosive chemist for the U. S. Bureau of Mines (1910–1933) from its inception to his own retirement.

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Munroe's name is most widely associated with the "Munroe effect" by which designs upon a block of explosive can be transmitted to metallic surfaces. Examples of this phenomenon prepared by Munroe himself are preserved in a fire-screen at the Cosmos Club in Washington and very large and remarkable extensions of this principle by Imperial Chemical Industries, Ltd., were shown at the 1948 Scientific Information Conference of the Royal Society at London. He also invented (U. S. 489,684, Jan. 10, 1883) "Indurite," a variety of smokeless powder which comprised an important advance at the time and was specifically commended by President Harrison in his farewell message to Congress. While still at Harvard he invented the platinum felt filter or Munroe crucible.

Munroe was the last surviving charter member of the American Chemical Society (founded in 1876), its president in 1898–1899, and was instrumental in the establishment of the principle of local sections and general meetings, the first of which later was held in Newport, Rhode Island, Aug. 6–7, 1890, during Munroe's duty there. He served continuously as associate editor on explosives for Chemical Abstracts for 32 years (1907–1939), and wrote nearly 300 articles and reports. Although absolutely fearless in the handling and investigation of explosives for 60 years, he took such care and precautions that he never suffered a serious accident.

P_1B J. Am. Chem. Soc. *61*, 1301–1316 (1939) (incl. bibliog.): P_3B Ind. Eng. Chem. *15*, 648–649 (1923): P_1B J. Chem. Education *4*, 276–277 (1927): P_3B J. Chem. Education *5*, 1484–1485 (1928): P_3B Ind. Eng. Chem., News Ed. *14*, 223 (1936); *16*, 647 (1938): B Science *89*, 26–27 (1939): P_3B Chemist *15*, 385–389 (1938): P_1B Explosives Engineer *1*, 2–3 (1923): B J. Chem. Soc. *1939*, 731–732: P_3B Z. ges. Schiess-u. Sprengstoffw. *24*, 121–124 (1929); *34*, 111 (1939): B Gen. Sci. Quart. *10*, 479–491 (1926): P_3B Natl. Cycl. Am. Biog. *29*, 334 (1941).

Jones, William

Born 1675 in the parish of Llanfihangel in the Angelsey island county of North Wales; died July 3, 1749, in London.

Jones was a mathematician and teacher. He was a friend both of Sir Isaac Newton and of Edmund Halley the astronomer. His writings include both navigation and general mathematics. In a "New Introduction to the Mathematics" (1706) he first employed the symbol π for the circle ratio. In 1711 he was one of a committee ap-

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pointed by the Royal Society of London to decide who had invented the infinitesimal calculus.

B Natl. Dict. Biog. *30*, 173–174 (1892).

OSLER, SIR WILLIAM

Born July 12, 1849, at Bond Head, Tecumseth County, Ontario, Canada (about 50 miles north of Toronto); died Dec. 29, 1919, at Oxford, England.

Osler's teaching and personality have strongly influenced the progress of medical science. After receiving his M.D. (1872) from McGill University and spending several years (1872–1874) in Europe, he became (1875–1884) professor at McGill Medical School, then professor of medicine (1884–1889) at the University of Pennsylvania, physician-in-chief at Johns Hopkins Hospital and professor of medicine at Johns Hopkins University at Baltimore, Maryland (1889–1905), and finally Regius professor of medicine at Oxford University, England (1905–1919).

Osler was the author of more than 730 articles and books, a bibliography of which, assembled by M. W. Blogg, appeared in the Bulletin of Johns Hopkins Hospital for July 1919. These included the Principles and Practice of Medicine (1891) which has since passed through many editions (11th, 1930) and translations. It was the perusal of this book by Rev. F. T. Gates, advisor to Mr. John D. Rockefeller, that led to the latter's heavy endowments of higher medicine and education.

It has been said of Osler by his one-time colleague, Dr. William Henry Welch, that at the time of his death, "he was probably the greatest figure in the medical world, the best-known, the most influential, the most beloved." The two volumes, "Life of William Osler", (1925) by the distinguished surgeon, Harvey Cushing, received the Pulitzer prize for biography. Osler was made a baronet in 1911. As he directed, his ashes rest in the Osler Memorial Library of McGill Medical School at Montreal.

P_1B Proc. Roy. Soc. (London) *92-B*, xvii–xxiv (1921): B Proc. Am. Acad. Arts Sci. *57*, 496–499 (1921–2): B Dict. Am. Biog. *14*, 83–87 (1934).

REVERDIN, FREDERIC

Born July 17, 1849, at Cologny, near Geneva, Switzerland; died Feb. 26, 1931, at age 82.

Reverdin entered (1869) the Federal Polytechnicum in Zurich under

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Emil Kopp and Victor Meyer and during this period became a close friend of E. Noelting with whom he later extensively collaborated. After brief sojourns in Berlin and at Heidelberg, he became (1872) research chemist for a dyestuff factory established by P. Monnet at La Plaine near Geneva (later to become the Societé Chimique des Usines du Rhone) where he was rejoined (1877) by Noelting. After 14 years Reverdin transferred to Meister Lucius Brüning at Höchst for a 15-year period. His final association was with l'Ecole de Chimie at Geneva where for 23 years (1907–1930) he remained. On his 75th anniversary both the Federal Polytechnicum and the University of Geneva awarded him honorary doctorates. He was Swiss delegate to the 7th Congress of Applied Chemistry in London (1909) and the 8th in New York (1912).

Reverdin's connection with the dyestuff industry at a period when the rapid developments of organic chemistry were stimulating its phenomenal growth led to a wide variety of publications both on dyestuffs and the structure and purity of their intermediates. Current students are constantly being led to his publications not only in Swiss journals but also those of France, England, and Germany. He was early concerned with studies of the triphenylmethane colors and with the manufacture of alkyl chlorides from the alcohols with hydrochloric acid under pressure. He discovered [Bull. soc. chim. (3) *15*, 638–646 (1896)] the peculiar migration of iodine occurring during the nitration of p-iodoanisole and was led to a long series of investigations on the nitration of variously substituted phenols, and to his studies of the behavior of nitramines with sulfuric acid.

With his friend de la Harpe he translated (1878) to the French the 10th German edition of Fittig's *Textbook of Organic Chemistry*, and prepared (1880) with Noelting the *Tables of Naphthalene Derivatives* subsequently to pass (1894) through a second edition and eventual revision (1927) in the two volumes by Van der Kam.

P$_1$B Helv. Chim. Acta *14*, 1046–1067 (1931): B Ber. *64-A*, 106–107 (1931).

Meldola, Raphael

Born July 19, 1849, at Islington, London; died Nov. 16, 1915.

Meldola came of an ancient Sephardic family of Spanish and Portuguese Jews whose genealogy could be traced unbroken through 16 generations back to Isaiah Meldola (1282–1340) of Toledo. He entered (1866) the Royal College of Chemistry as pupil of Edward Frankland; then (1868–1871) was assistant in the private laboratory

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of John Stenhouse. In 1872 he rejoined Frankland on the staff of the Royal College (meantime transferred to South Kensington) where he also worked with (Sir) Norman Lockyer for 3 years on spectrum analysis and photography.

About this time he spent 8 years in industrial dyestuff work during which he discovered (1879) the first oxazine dyestuff (still known as Meldola's blue) and made other substantial contribution to synthetic coloring matters.

In 1885 Meldola was appointed professor of chemistry at Finsbury Technical College (Sylvanus Thompson being simultaneously called to the chair of physics) where he remained (1885–1915) for the ensuing 30 years of his life and where he numbered among his students such men as (Sir) M. B. Forster, (Sir) G. T. Morgan, and (Sir) W. J. Pope. His researches effected great progress in knowledge of structure and isomerism of diazoamino compounds, of *o*-amino and *o*-hydroxyazo compounds, imidazoles, and displacement of groups in aromatic compounds. He discovered 1-amino-2-naphtholsulfonic acid-6 whose salt is the photographic developer "Eikonogen" [J. Soc. Chem. Ind. *8*, 958–959 (1889)].

His first academic recognition was an honorary Sc.D. from the University of Oxford (1910) but he received many distinguished medals and offices. His earliest work was in the field of biology and nature study and he was secretary of the Entomological Society (London) (1886–1880) and its president (1895). He was president of the (British) Chemical Society (1905–1907), the Society of Dyers and Colourists (1907–1908) (succeeding W. H. Perkin), the Society of Chemical Industry (1908–1909), and the Institute of Chemistry (1912–1915).

P_1B Proc. Roy Soc. (London) *93-A*, XXIX–XXXVII (1916–7): B J. Chem. Soc. *111*, 349–359 (1917): B Nature *96*, 345–347 (1915–6): B J. Soc. Dyers and Colourists *31*, 260–262 (1915): B Ber. *48*, 2097 (1915): P_1B Findlay and Mills "British Chemists" (Chem. Soc. London 1947), pp. 96–125.

KJELDAHL, JOHAN GUSTAV CHRISTOFFER THORSAGER

Born Aug. 16, 1849, in Jaegerspris, in northern part of the Danish island of Zealand; died July 18, 1900, at Tisvilde, Zealand, Denmark.

Kjeldahl took his baccalaureate degree (1867) at the gymnasium of Roeskilde, then went for further study and chemical training to both the University and Technische Hochschule of near-by Copenhagen. After passing his examinations (1873) with special distinction he

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briefly assisted C. F. Barfoed at the chemical laboratory of the Royal Danish Agricultural School but soon (October, 1876) transferred to the newly established Carlsberg Laboratory in Copenhagen, where he spent the remaining 25 years of his life.

Although Kjeldahl made numerous investigations on other topics such as the behavior of enzymes, the determination of various sugars and mixtures of sugars by the Fehling titration method, and the optical rotation of vegetable proteins, his name is most widely associated with the method which he devised for the quantitative determination of nitrogen, and with the particular type of long-necked glass flask which it employs. The method was first disclosed in a lecture on March 7, 1883, but was published soon afterward [Z. anal. Chem. *22*, 366–382 (1883)]. In 1894 he was awarded an honorary doctorate by the University of Copenhagen.

The Kjeldahl determination of nitrogen is based upon decomposition of the organic sample with hot concentrated sulfuric acid in the presence of suitable catalysts; the nitrogen is converted to ammonia which is subsequently liberated with alkali and distilled into a known excess of standard acid. After simple titration of the residual acidity the amount of ammonia (and therefore the nitrogen in the original sample) is readily calculable. The method is much simpler and more accurate than combustion but cannot be applied to as wide a range of nitrogen compounds.

P_1B Ber. *33*, 3881–3888 (1900): P_3B J. Chem. Education *11*, 457–462 (1934).

HELL, CARL MAGNUS VON

Born Sept. 8, 1849, at Stuttgart, Germany; died Dec. 11, 1926, at age 77.

C. M. von Hell was a student of Fehling at Stuttgart and of Erlenmeyer at Munich; in 1883 he succeeded the former.

In 1889 he effected the synthesis of the paraffin hydrocarbon $C_{60}H_{122}$ which during his lifetime was the highest known alkane. He was much interested in acids and published numerous studies of those of the dibasic type. His name is most frequently associated, however, with the so-called Hell-Volhard-Zelinsky procedure for the bromination of acids in the presence of phosphorus. The initial publication of Hell [Ber. *14*, 891–893 (1881)] was independently confirmed by those of Volhard [Ann. *242*, 141–163 (1887)] and Zelinsky [Ber. *20*, 2026 (1887)].

B Ber. *60-A*, 54–55 (1927).

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PAVLOV, IVAN PETROVICH

Born Sept. 27, 1849 (new style) (Sept. 14, old style), at Ryazan (about 100 miles southeast of Moscow); died Feb. 27, 1936, at age 86.

Regarded as one of the greatest physiologists of last and present centuries, Pavlov attained a unique and almost legendary position in science. His early training in science at the University of St. Petersburg was extended by studies at the Military Medical Academy, where under the physiologist Cyon (Tsion) (the discoverer of the depressor nerve) he enthusiastically entered upon physiological research during which he discovered (1888) the secretory nerves of the pancreas. After being licensed in medicine (1879), obtaining his M.D. degree (1883), and spending several years in Germany under Ludwig at Leipzig and Heidenhain at Breslau, he became (1890) director of the physiological department of the newly established Institute of Experimental Medicine at St. Petersburg. Without giving up this post he also served (1897–1914) as professor of physiology at the Military Medical Academy, while in 1907 he became one of four scientific members of the St. Petersburg Academy. These concurrent appointments resulted in his work being carried on in three laboratories.

Pavlov's scientific career embraced three distinct phases. The first was concerned with studies of the circulatory system with particular reference to the efferent nerves of the heart and with heart rate and led to his discovery of the pressor influence of the vagus nerve. The second (1888–1906) comprised his epochal studies on secretion and digestion, resulted in some 130 scientific communications from his laboratories and culminated in the award to him of the 1904 NOBEL PRIZE FOR PHYSIOLOGY AND MEDICINE, "in recognition of his work on the physiology of digestion which essentially reformed and extended scientific knowledge in this field." The third period (1907–1936), primarily devoted to his studies of conditioned reflexes, yielded results which have had profound influence upon scientific understanding of the physiology of the brain and sense organs and upon the sciences of psychology and psychiatry.

P_1B Obit. Notices Fellows Roy. Soc. (London) *2*, 1–18 (1936): P_1B Nature *115*, 1–3 (1925): B Nature *137*, 483–485 (1936): B Science *83*, 351–353 (1936): B Proc. Roy. Soc. Edinburgh *56*, 264–275 (1935–6): B Nature *154*, 385–388 (1944): B Bull. soc. sci. hyg. aliment. *24*, 344–362 (1936).

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SCHÖNBEIN, CHRISTIAN FRIEDRICH

Born Oct. 18, 1799, at Metzingen, Swabia (Württemberg), Germany; died August 29, 1868, at Sauersberg, near Baden-Baden.

Schönbein's early contacts with chemistry were as helper in various chemical factories, including a brief period in that of Johann Gottfried Dingler, who enlisted his assistance with the famous "Polytechnisches Journal", then (1820) just being launched. With various interruptions he attended both the University of Tübingen and that of Erlangen and subsequently spent two years in England and one in Paris. In 1828 he was called to the University of Basle in Switzerland where in 1835 he became professor of physics and chemistry. When (1852) a separate chair of physics was created, Schönbein continued to occupy that of chemistry for the rest of his life, thus completing 40 years continuously at Basle.

Schönbein discovered (1839) ozone and gave it that name; this formed part of a 29-year study of oxygen which brackets his name with those of Priestley, Scheele and Lavoisier. On May 7, 1846, at a meeting of the Society of Scientific Research at Basle, he announced the discovery of guncotton. Although the action of nitric acid upon paper, linen and cotton fibers had earlier been examined by Pelouze, Schönbein was the first to employ a mixture of nitric and sulfuric acids, and actually to demonstrate the use of the product as a propellant in guns and as an explosive in mines, and is therefore regarded by the explosives industry as the discoverer of nitrocellulose. In the course of studies of the solubility of his mixed cellulose nitrates, Schönbein found that evaporation of an ether-alcohol solution left a flexible film, and the first medical use of this as a coating (collodion) was made at Schönbein's suggestion by his friend Dr. Jung of Basle.

Schönbein was an active correspondent with many other contemporary scientists and his correspondence with Berzelius, with Liebig, and with Faraday has been published in book form.

P_2B J. Chem. Education *6*, 410, 432–440, 677–685 (1929): P_2 ibid. *7*, 1832–1833 (1930): B J. Chem. Soc. *22*, X–XIII (1869): B Ann. Repts. Smithsonian Inst. *23*, 185–192 (1868): P_1B Bugge "Das Buch der Grossen Chemiker" *1*, 458–468 (1929) B Nitrocellulose *1*, 1–2 (1930).

RUTHERFORD, DANIEL

Born Nov. 3, 1749, at Edinburgh, Scotland; died Dec. 15, 1819.

This notable Scotch physician was an uncle of the distinguished novelist and poet, Sir Walter Scott. A student of William Cullen and

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Joseph Black he succeeded (1786) John Hope in chair of botany at University of Edinburgh, where he remained 33 years.

Just as the dissertation of his celebrated professor, Joseph Black (published June 11, 1754) had contained the discovery of carbon dioxide, so that of Daniel Rutherford (dated Sept. 12, 1772, at age 23) made clear the existence of nitrogen (phlogisticated air) as distinct from carbon dioxide (fixed air). The only known copy of this thesis is preserved in the British Museum but Crum-Browne's translation of its Latin text has been published [Dobbin, J. Chem. Education *12*, 370–375 (1935)]. The new gas was also independently discovered about the same time by Scheele, Priestley, and Cavendish, but the name nitrogen was not given to it until 18 years later (1790) by Chaptal. Rutherford also invented a maximum and minimum thermometer still described in many modern physics textbooks, but the discovery of nitrogen was his only contribution to chemistry.

It is a curious and unexplained coincidence that Dr. Rutherford's mother, he himself, and a sister all died suddenly within scarcely more than a single week.

P_3B J. Chem. Education *11*, 101–107 (1934); *9*, 219–221 (1932)· B Science Progress *29*, 650–660 (1935): Dict. Natl. Biog. *50*, 5–6 (1897).

DANA, EDWARD SALISBURY

Born Nov. 16, 1849, New Haven, Conn.; died June 16, 1935, at age 85.

E. S. Dana was the son of James Dwight Dana (himself an eminent mineralogist) and the grandson of Benjamin Silliman. After B.S. (1870) from Yale he studied (1870–1872) with G. J. Brush at Sheffield Scientific School, then (1873) with Bunsen at Heidelberg and (1874) with Tschermak at Vienna. He received M.A. (1874) and Ph.D. (1876) from Yale, his dissertation for the latter representing the first important application in America of microscopical petrography. Since at the time Yale had no staff opening in mineralogy, Dana first held (1876–1879) a tutorship in mathematics, physics, and chemistry. After 11 years (1879–1890) as professor of natural philosophy he became professor of physics in which capacity he served (1890–1917) until retirement despite the fact that his outstanding work was exclusively in mineralogy.

E. S. Dana's fame rests mainly on his books. His first volume at age 28 (1877) was the "Textbook of Mineralogy," whose second edition (1898) carried an exposition of optical mineralogy long without equal. Two further editions (1921, 1932) were later prepared by W. E. Ford. His greatest monument, however, was the 6th edition (1892) of his

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father's "System of Mineralogy," universally recognized as one of the most remarkable scientific volumes ever published. To keep the system up to date, three appendices (1899, 1909, 1915) have been issued, and a 7th edition is contemplated under supervision of Profs. Palache and Ford.

The American Journal of Science, founded (1818) by Benjamin Silliman, was carried on after his retirement (1885) by the Danas (father and son); after the death of James Dana, son Edward was editor for 31 years (1895–1926). For a history of this remarkable journal, thus under the leadership of grandfather, father, and grandson continuously for 108 years (and still being published) see the article by C. S. Dana in celebration of its centenary [Am. J. Sci. (4) *46*, 1–44 (1918)].

Dana became (1925) honorary president for life of the American Mineralogical Society and at the time of his death had been a member of the National Academy of Science for 51 years, a span then exceeded by only one other. Dana and his wife spent their summers at Seal Harbor, Mt. Desert Island, Maine, where both are buried.

P_1B Am. J. Sci. (5) *30*, 161–176 (1934): P_1B Proc. Geol. Soc. Am. *1935*, 201–214 (incl. bibliog.): P_1B Biog. Memoirs Natl. Acad. Sci. *18*, 349–365 (1938) (incl. bibliog.): P_3B Am. Mineral. *21*, 173–174 (1936): P_3B Mineralog. Mag. *24*, 281–283 (1934–7): B Science 82, 342–344 (1935): B Proc. Am. Acad. Arts Sci. *70*, 517–518 (1934–5): B Quart. J. Geol. Soc. London *92*, LXXXIX–XCI (1936): B Dict. Am. Biog. *21*, 221–222 (1944): B Natl. Cycl. Am. Biog. *30*, 332 (1943).

Fleming, Sir John Ambrose

Born Nov. 29, 1849, at Lancaster, Lancashire, England; died April 18, 1945, at Sidworth, Devon, England, at age 95.

Fleming was primarily an electrical engineer and a physicist but his early training was chemical. He entered (1866) University College, London, receiving B.Sc. in 1870, and (1871) Royal College at So. Kensington as chemical student of Frankland and his then assistant, Meldola, working chiefly on organometallic compounds. He invented a form of voltaic cell [Proc. Phys. Soc. London *1*, 1–12 (1874)] comprising not only his first publication but also the first paper presented before the newly formed Physical Society of London of which he became the last surviving charter member. He entered (1877) St. John's College at Cambridge University, where he attended the last two years of Maxwell's lectures and worked in the Cavendish laboratory, mainly on resistance standards. After a period (1879–1884) of varied consulting in industry, he became the first professor of electrical

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engineering at University College, London, where he remained (1885–1926) for 41 years.

Fleming was a pioneer in the application of electrical science to problems of electric lighting, wireless telegraphy and telephony. He devised a standard lamp for photometric measurements, carried out with Dewar studies on the magnetic and electrical properties of metals at low temperatures, and constructed (1883) the first direct reading potentiometer. He designed for Marconi the power transmitter at Poldhu, Cornwall, which on Dec. 12, 1901, effected the first transatlantic wireless communication. In 1904 he developed the so-called "Edison effect" (1883) into the first thermionic vacuum tube rectifier [Brit. Pat. 24,850, Nov. 16, 1904; U. S. 803,684, April 19, 1905] or Fleming valve [see Franklin Medal address, Science *81*, 625–628 (1935)], the precursor of the amplifying triode tube first described four years later by Lee DeForest in America. Fleming's invention also preceded by two years the invention by H. H. C. Dunwoody of the first (carborundum) crystal detector of wireless signals.

Fleming was author of many books and articles on electrical subjects and (1934) of an autobiography, "Memoirs of a Scientific Life." He received many distinguished medals, was elected to Royal Society in 1892, and knighted in 1929.

P_1B Obit. Notices Fellows Roy. Soc. (London) *5*, 231–242 (1945): P_3B J. Telev. Soc. *4*, 266–273 (1946): B J. Inst. Elec. Engrs. *92*, I 467–468 (1945): B Nature *155*, 662–663 (1945): B Proc. Phys. Soc. London *57*, 581–584 (1945).

WAGNER, GEORG

Born Nov. 29, 1849, at Kasan, Russia (about 360 miles east of Moscow); died Nov. 27, 1903, at Warsaw, Poland.

Wagner's father was German, his mother Russian. At age 16 he entered University of Kasan to study law but after two years abandoned this intention to become a chemical pupil of A. Saytzeff. On completion of his course he went (1874) to St. Petersburg to work under Butlerow. In 1882 after the death of his young wife he removed to the Hochschule at Novo Alexandria in the Lublin province of Russian Poland. Shortly thereafter (1886) he was appointed assistant professor of organic chemistry at the University of Warsaw, from which he subsequently (1902) withdrew upon completion of the new laboratory of the Warsaw Polytechnic Institute, where he became associate professor and head of the chemical division.

His chemical work comprised three recognizable periods. The first (1875–1885), begun at Kasan and continued at St. Petersburg and

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Novo Alexandria, was mainly concerned with the synthesis of secondary alcohols and studies of their oxidation to ketones and culminated with the Master's degree of St. Petersburg. The second (1886–1889) comprised studies on the oxidation of unsaturated hydrocarbons to glycols by means of dilute aqueous potassium permanganate, some parts of it comprising Wagner's doctoral dissertation (1888) at the University of Warsaw. The third period (1890–1903) was characterized by extensive studies in the terpene series and, among other results, led to his establishment of the first correct structures for limonene, pinene, and camphene. By most students of organic chemistry, however, his name is associated with the Wagner (or Wagner-Meerwein) rearrangement.

P_1B Ber. *36*, 4591–4613 (1903).

BLACK, JOSEPH

Born April 16, 1728, in Bordeaux, France; died Dec. 6, 1799, at Edinburgh, Scotland.

Although born in France, Black was of Scottish parents. In 1746 he matriculated at the University of Glasgow as a student of William Cullen whom he later succeeded. In 1750 he began the study of medicine at the University of Edinburgh, where in 1754 his dissertation comprised the discovery of "fixed air" (carbon dioxide) [for Crum-Brown's translation of this Latin thesis, see J. Chem. Education *12*, 225–228, 268–273 (1945)], the first recognized pure gas. Note, however, that another twenty-five years elapsed before its true composition was established (1779) by Lavoisier.

Black served (1756–1766) as professor of chemistry and medicine at the University of Glasgow and as professor of chemistry (1766–1799) at the University of Edinburgh. He was regarded as a perfect lecturer and his manuscript notes have been published [Ann. Sci. *1*, 101–110 (1936)]. He was the first to recognize (1761) the existence and significance of "latent heat" (to which he gave this name) and to study "specific heat," i. e., to invent and use the calorimeter.

Upon the suggestion of Lavoisier, Black was named by the French Academy of Sciences as one of its eight foreign members. He never married. His grave in Greyfriars Churchyard at Edinburgh has been marked by a memorial tablet. [P_3 J. Chem. Education *10*, 716 (1933)].

P_1B Isis *25*, 372–390 (1936): P_3B J. Chem. Education *8*, 2138–2139 (1931); *13*, 503–504 (1936): P_2 *11*, 485 (1934): B Chemistry and Industry *20*, 530–531 (1942): B Chem. Ztg. *52*, 913 (1928): B School Sci. Rev. *18*, 45–49 (1936): B Dict. Natl. Biog. *5*, 109–112 (1886): P_3B Chem. Weekblad *16*, 168–178 (1919) (in Dutch).

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37 Gustavus John Esselen ..... Swampscott
33 Louis Frederick Fieser ..... Belmont
35 Louis Harris ..... Belmont
36 Albert Baird Hastings ..... Brookline
38 Robert Casad Hockett ..... Concord
36 Ernest Hamlin Huntress ..... Melrose Highlands
19 Frederick George Keyes ..... Cambridge
33 George Bogdan Kistiakowsky ..... Cambridge
15 Charles August Kraus ..... Providence, R. I.
14 Arthur Becket Lamb ..... Brookline
18 Irving Langmuir ..... Schenectady, N. Y.
15 Warren Kendall Lewis ..... Newton
23 Duncan Arthur MacInnes ..... New York, N. Y.
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35 Nicholas Athanasius Milas ..... Belmont
36 Avery Adrian Morton ..... Watertown
19 Edward Mueller ..... Cambridge
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45 John Lawrence Oncley ..... Newtonville
44 Linus Carl Pauling ..... Pasadena, Cal.
39 Clifford Burrough Purves ..... Montreal, Can.
14 Martin André Rosanoff ..... Mt. Lebanon, Pa.
28 George Scatchard ..... Cambridge
32 Walter Cecil Schumb ..... East Milton
15 Miles Standish Sherrill ..... Brookline
20 Harry Monmouth Smith ..... Brookline
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19 Robert Seaton Williams ..... Belmont
44 Edgar Bright Wilson, Jr. ..... Cambridge
48 Robert Burns Woodward ..... Cambridge
41 Ralph Chillingworth Young ..... Arlington

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06 Comfort Avery Adams ..... Philadelphia, Pa.
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33 Harold Kilbrith Barrows ..... Winchester
31 Charles Harold Berry ..... Belmont
41 Edward Lindley Bowles ..... Wellesley
25 Vannevar Bush ..... Washington, D. C.
48 John Chipman ..... Winchester
45 Hardy Cross ..... New Haven, Conn.
34 Otto Gustav Colbiornsen Dahl ..... Boston
34 Chester Laurens Dawes ..... Cambridge
34 Jacob Pieter Den Hartog ..... Wellesley Hills
43 Bradley Dewey ..... Cambridge
20 Theodore Harwood Dillon ..... Washington, D. C.
41 Charles Stark Draper ..... Newton
22 Gano Dunn ..... New York, N. Y.
21 William Frederick Durand ..... Palo Alto, Cal.
46 Howard Wilson Emmons ..... Sudbury
27 Gordon Maskew Fair ..... Cambridge
48 Ivan Alexander Getting ..... Belmont
32 Glennon Gilboy ..... Lincoln
48 Edwin Richard Gilliland ..... Arlington
32 Albert Haertlein ..... Watertown
40 Harold Locke Hazen ..... Belmont
44 Arthur Robert von Hippel ..... Weston
36 Murray Philip Horwood ..... Cambridge
48 Hoyt Clarke Hottel ..... Winchester
34 Jerome Clarke Hunsaker ..... Boston
23 James Robertson Jack ..... Watertown
11 Dugald Caleb Jackson ..... Cambridge
30 Frank Baldwin Jewett ..... Short Hills, N. J.
01 Lewis Jerome Johnson ..... Cambridge
48 Theodore von Kármán ..... Pasadena, Cal.
37 Joseph Henry Keenan ..... Belmont
32 Ralph Restieaux Lawrence ..... Belmont
23 William Henry Lawrence ..... Jamaica Plain
38 John Moyes Lessells ..... Brookline
48 William Henry McAdams ..... Newton
37 Charles Winters MacGregor ..... Belmont

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44 Richard von Mises.....Cambridge
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20 Frederick Law Olmsted.....Elkton, Md.
28 Langdon Pearse.....Chicago, Ill.
13 Harold Pender.....Wynnewood, Pa.
30 Greenleaf Whittier Pickard.....Newton Center
41 Reinhold Rüdenberg.....Belmont
48 Thomas Kilgore Sherwood.....Wellesley
39 C. Richard Soderberg.....Weston
14 Charles Milton Spofford.....Boston
45 Frederick Emmons Terman.....Palo Alto, Cal.
[28] 44 Karl Terzaghi.....Winchester
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48 Walter Gordon Whitman.....Concord
45 John Benson Wilbur.....Belmont
40 John Wulff.....Cambridge
41 Vladimir Kosma Zworykin.....Princeton, N. J.

CLASS II—NATURAL AND PHYSIOLOGICAL SCIENCES—216

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41 Alan Mara Bateman.....New Haven, Conn.
46 Roland Frank Beers.....Lincoln
38 Marland Pratt Billings.....Wellesley
21 Norman Levi Bowen.....Chicago, Ill.
16 Isaiah Bowman.....Baltimore, Md.
33 Charles Franklin Brooks.....Milton
29 Kirk Bryan.....Cambridge
48 Arthur Francis Buddington.....Princeton, N. J.
45 Martin Julian Buerger.....Lincoln
33 Frank Morton Carpenter.....Lexington
34 Sterling Price Fergusson.....Milton
42 Russell Gibson.....Belmont
14 Louis Caryl Graton.....Cambridge
17 Herbert Ernest Gregory.....Honolulu, T. H.
21 William Jackson Humphreys.....Washington, D. C.
46 Cornelius Searle Hurlbut, Jr.....Belmont
44 Columbus O'Donnell Iselin.....Woods Hole
02 Thomas Augustus Jaggar.....Honolulu, T. H.
48 Adolph Knopf.....New Haven, Conn.
25 Esper Signius Larsen, Jr.....Belmont
15 Andrew Cowper Lawson.....Berkeley, Cal.
16 Charles Kenneth Leith.....Madison, Wis.
31 George Francis McEwen.....La Jolla, Cal.
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34 Walter Harry Newhouse ..... Chicago, Ill.
22 Austin Flint Rogers ..... Palo Alto, Cal.
34 Carl-Gustaf Arvid Rossby ..... Chicago, Ill.
19 Waldemar Theodore Schaller ..... Washington, D. C.
48 George Gaylord Simpson ..... New York, N. Y.
45 Henry Crosby Stetson ..... Belmont
41 Chester Stock ..... Pasadena, Cal.
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35 Derwent Stainthorpe Whittlesey ..... Cambridge
15 Bailey Willis ..... Palo Alto, Cal.
15 Frederick Eugene Wright ..... Washington, D. C.

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30 LeRoy Abrams ..... Palo Alto, Cal.
11 Oakes Ames ..... North Easton
34 Edgar Anderson ..... St. Louis, Mo.
15 Irving Widmer Bailey ..... Cambridge
00 Liberty Hyde Bailey ..... Ithaca, N. Y.
40 Albert Francis Blakeslee ..... Northampton
98 Douglas Houghton Campbell ..... Palo Alto, Cal.
48 Edward Sears Castle ..... Cambridge
46 Ralph Erskine Cleland ..... Bloomington, Ind.
16 Bradley Moore Davis ..... Ann Arbor, Mich.
35 Bernard Ogilvie Dodge ..... New York, N. Y.
41 Arthur Johnson Eames ..... Ithaca, N. Y.
12 Alexander William Evans ..... New Haven, Conn.
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45 Dennis Robert Hoagland ..... Berkeley, Cal.
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27 George James Peirce ..... Palo Alto, Cal.
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14 Alfred Rehder ..... Jamaica Plain
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32 Ralph Hartley Wetmore ..... Cambridge

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46 George Wells Beadle ..... Pasadena, Cal.
09 Francis Gano Benedict ..... Machiasport, Me.
11 Henry Bryant Bigelow ..... Concord
14 Robert Payne Bigelow ..... Brookline
35 Charles Henry Blake ..... Lincoln
20 William T. Bovie ..... Fairfield, Me.
24 Edward Allen Boyden ..... Minneapolis, Minn.
16 John Lewis Bremer ..... Boston
28 John Wymond Miller Bunker ..... Belmont
00 William Ernest Castle ..... Berkeley, Cal.
29 Lemuel Roscoe Cleveland ..... Jamaica Plain
26 Edwin Joseph Cohn ..... Cambridge
14 Edwin Grant Conklin ..... Princeton, N. J.
23 Manton Copeland ..... Brunswick, Me.
27 William John Crozier ..... Belmont
17 Joseph Augustine Cushman ..... Sharon
29 Hallowell Davis ..... St. Louis, Mo.
33 Alden Benjamin Dawson ..... Belmont
25 Samuel Randall Detwiler ..... New York, N. Y.
43 David Bruce Dill ..... Edgewood Arsenal, Md.
48 Edward Adelbert Doisy ..... St. Louis, Mo.
25 Herbert McLean Evans ..... Berkeley, Cal.
48 Wallace Osgood Fenn ..... Rochester, N. Y.
34 Cyrus Hartwell Fiske ..... Lexington
34 John Farquhar Fulton ..... New Haven, Conn.
48 Herbert Spencer Gasser ..... New York, N. Y.
47 Arnold Lucius Gesell ..... New Haven, Conn.
31 William King Gregory ..... New York, N. Y.
48 Edmund Newton Harvey ..... Princeton, N. J.
36 Frederick Lee Hisaw ..... Belmont
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27 Axel Leonard Melander . . . . . Riverside, Cal.
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48 George Wald . . . . . Belmont
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36 Oswald Theodore Avery . . . . . New York, N. Y.
29 James Bourne Ayer . . . . . Milton
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21 Rufus Cole . . . . . Mount Kisco, N. Y.
31 Eugene Floyd DuBois . . . . . New York, N. Y.
46 John Franklin Enders . . . . . Boston
45 James Morison Faulkner . . . . . Brookline
44 Maxwell Finland . . . . . Squantum
33 Reginald Fitz . . . . . Brookline
27 James Lawder Gamble . . . . . Brookline
22 Joseph Lincoln Goodale . . . . . Ipswich
45 Thomas Hale Ham . . . . . Brookline
21 Ross Granville Harrison . . . . . New Haven, Conn.
47 Sanford Burton Hooker . . . . . West Roxbury
27 Percy Rogers Howe . . . . . Belmont
33 Edgar Erskine Hume . . . . . Frankfort, Ky.
34 Henry Jackson, Jr. . . . . Chestnut Hill
46 Charles Alderson Janeway . . . . . Weston
12 Elliott Proctor Joslin . . . . . Boston
43 Chester Scott Keefer . . . . . Brookline
23 Roger Irving Lee . . . . . Brookline
42 Samuel Albert Levine . . . . . Newton Center
29 Edwin Allen Locke . . . . . Wilton, N. H.
28 Warfield Theobald Longcope . . . . . Baltimore, Md.
32 Fred Bates Lund . . . . . Newton Center
40 William de Berniere MacNider . . . . . Chapel Hill, N. C.
44 William Malamud . . . . . Worcester
34 Leroy Matthew Simpson Miner . . . . . Newtonville
26 George Richards Minot . . . . . Brookline
28 William Lorenzo Moss . . . . . Athens, Ga.
28 John Howard Mueller . . . . . West Roxbury
37 Walter Walker Palmer . . . . . New York, N. Y.
27 Joseph Hershey Pratt . . . . . Brookline
35 Tracy Jackson Putnam . . . . . New York, N. Y.
34 William Carter Quinby . . . . . Brookline
47 Francis Minot Rackemann . . . . . Boston
48 John Rock . . . . . Roslindale
34 Arthur Hiler Ruggles . . . . . Providence, R. I.
39 Frederick Fuller Russell . . . . . Brookline
39 William Thomas Salter . . . . . New Haven, Conn.
33 George Cheever Shattuck . . . . . Brookline
47 James Stevens Simmons . . . . . Boston
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47 Shields Warren ..... West Newton
27 Joseph Treloar Wearn ..... Cleveland, O.
40 Paul Dudley White ..... Brookline
12 Simeon Burt Wolbach ..... South Sudbury

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Section 1—*Jurisprudence*—35

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36 Stoughton Bell ..... Cambridge
33 Harry Augustus Bigelow ..... Chicago, Ill.
36 Claude Raymond Branch ..... Providence, R. I.
48 Charles Allerton Coolidge ..... Belmont
33 John Dickinson ..... Philadelphia, Pa.
38 Robert Gray Dodge ..... Boston
31 Fred Tarbell Field ..... Newton
40 Lon Louvois Fuller ..... Cambridge
39 Herbert Funk Goodrich ..... Philadelphia, Pa.
33 Theodore Francis Green ..... Providence, R. I.
38 Frank Washburn Grinnell ..... Boston
41 Erwin Nathaniel Griswold ..... Belmont
39 John Loomer Hall ..... Boston
39 Augustus Noble Hand ..... New York, N. Y.
33 Learned Hand ..... New York, N. Y.
39 Albert James Harno ..... Urbana, Ill.
47 Mark DeWolfe Howe ..... Cambridge
38 Melvin Maynard Johnson ..... Brookline
38 James McCauley Landis ..... Washington, D. C.
32 Sayre Macneil ..... Pasadena, Cal.
32 Calvert Magruder ..... Cambridge
31 William DeWitt Mitchell ..... New York, N. Y.
31 Edmund Morris Morgan ..... Arlington
47 John Lord O'Brian ..... Washington, D. C.
36 Henry Parkman, Jr. ..... Boston
01 George Wharton Pepper ..... Philadelphia, Pa.
11 Roscoe Pound ..... Watertown
36 Stanley Elroy Qua ..... Lowell
32 Francis Bowes Sayre ..... Washington, D. C.
21 Austin Wakeman Scott ..... Cambridge
36 Sidney Post Simpson ..... Cambridge
39 Thomas Walter Swan ..... New York, N. Y.
43 Charles Edward Wyzanski, Jr. ..... Cambridge

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33 Edwin Montefiore Borchard.....New Haven, Conn.
46 Harvey Hollister Bundy.....Boston
40 Robert Granville Caldwell.....Belmont
32 William Richards Castle, Jr.....Washington, D. C.
32 Joseph Perkins Chamberlain.....New York, N. Y.
48 William Lockhart Clayton.....Washington, D. C.
33 Robert Treat Crane.....Baltimore, Md.
35 Tyler Dennett.....Hague, N. Y.
46 John Sloan Dickey.....Hanover, N. H.
27 William Cameron Forbes.....Norwood
44 Carl Joachim Friedrich.....Concord
34 Edgar Stephenson Furniss.....New Haven, Conn.
32 Joseph Clark Grew.....Washington, D. C.
35 Charles Grove Haines.....Los Angeles, Cal.
41 Hajo Holborn.....Hamden, Conn.
27 Arthur Norman Holcombe.....Cambridge
32 Philip Carryl Jessup.....New York, N. Y.
32 Charles Edward Merriam.....Chicago, Ill.
13 William Bennett Munro.....Pasadena, Cal.
47 William Phillips.....North Beverly
41 Gaetano Salvemini.....Cambridge
46 Robert Burgess Stewart.....Winchester
44 Sarah Wambaugh.....Cambridge
47 Sumner Welles.....Oxon Hill, Md.
43 Payson Sibley Wild, Jr.....Cambridge
32 William Franklin Willoughby.....Washington, D. C.
14 George Grafton Wilson.....Grafton, Vt.
48 Howard Eugene Wilson.....New York, N. Y.
27 Quincy Wright.....Chicago, Ill.
33 Henry Aaron Yeomans.....Harvard

CLASS III, SECTION 3—*Economics and Sociology*—56

36 James Waterhouse Angell.....New York, N. Y.
47 George Pierce Baker.....Boston
48 Richard Mervin Bissell, Jr.....Washington, D. C.
36 James Cummings Bonbright.....New York, N. Y.
43 Augusta Fox Bronner (Mrs. William Healy).....Boston
44 Douglass Vincent Brown.....Brookline
46 Theodore Henry Brown.....Cambridge
33 Harold Hitchings Burbank.....Cambridge
34 John Maurice Clark.....Westport, Conn.
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34 Ralph Evans Freeman ..... Cambridge
33 Sheldon Glueck ..... Cambridge
34 Robert Murray Haig ..... New York, N. Y.
41 Earl Jefferson Hamilton ..... Evanston, Ill.
45 Seymour Edwin Harris ..... West Acton
48 Bishop Carleton Hunt ..... Norwell
34 Frank Hyneman Knight ..... Chicago, Ill.
36 Roswell Cheney McCrea ..... Augusta, Ga.
34 Robert Morison MacIver ..... New York, N. Y.
32 Walter Wallace McLaren ..... Williamstown
45 William Rupert Maclaurin ..... Cambridge
36 Malcolm Perrine McNair ..... Cambridge
32 Leon Carroll Marshall ..... Chevy Chase, Md.
34 Richard Stockton Meriam ..... South Lincoln
32 Frederick Cecil Mills ..... New York, N. Y.
34 Arthur Eli Monroe ..... Cambridge
34 Edwin Griswold Nourse ..... Washington, D. C.
32 William Fielding Ogburn ..... Chicago, Ill.
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42 William Andrew Paton ..... Ann Arbor, Mich.
47 Fritz Jules Roethlisberger ..... Cambridge
37 Clyde Orval Ruggles ..... Cambridge
42 Paul Anthony Samuelson ..... Belmont
36 Thomas Henry Sanders ..... Cambridge
33 Josef Alois Schumpeter ..... Cambridge
43 Benjamin Morris Selekman ..... Cambridge
31 Pitirim Alexandrovich Sorokin ..... Winchester
41 Francis Trow Spaulding ..... Albany, N. Y.
31 Oliver Mitchell Wentworth Sprague ..... Cambridge
46 Harold Walter Stoke ..... Baton Rouge, La.
37 Harry Rudolph Tosdal ..... Belmont
31 Donald Skeele Tucker ..... Belmont
41 Robert Ulich ..... Cambridge
33 Abbott Payson Usher ..... Salem
34 Jacob Viner ..... Princeton, N. J.
38 T[homas] North Whitehead ..... Cambridge
32 John Henry Williams ..... Cambridge
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45 Edwin Sharp Burdell.....New York, N. Y.
41 Godfrey Lowell Cabot.....Boston
47 Thomas Dudley Cabot.....Weston
48 Erwin Dain Canham.....Newton
47 William Henry Claflin, Jr.....Belmont
48 Charles Woolsey Cole.....Amherst
43 Ada Louise Comstock (Mrs. Wallace Notestein).....New Haven, Conn.
48 Robert Cutler.....Boston
42 Donald Kirk David.....Boston
48 Herbert John Davis.....Northampton
38 Edmund Ezra Day.....Ithaca, N. Y.
32 Henry Sturgis Dennison.....Framingham
46 David Frank Edwards.....Cambridge
48 Carl Stephens Ell.....Newton
(28) 32 William Lusk Webster Field.....Milton
39 Ralph Edward Flanders.....Springfield, Vt.
38 Horace Sayford Ford.....Belmont
44 Raymond Blaine Fosdick.....New York, N. Y.
48 Francis Calley Gray.....Boston
35 Jerome Davis Greene.....Cambridge
(28) 32 Edward Jackson Holmes.....Topsfield
44 Ernest Martin Hopkins.....Hanover, N. H.
48 Carl Tilden Keller.....Boston
34 Henry Plimpton Kendall.....Sharon
44 James Rhyne Killian, Jr.....Wellesley Hills
39 Morris Evans Leeds.....Philadelphia, Pa.
48 David Eli Lilienthal.....Washington, D. C.
34 Clarence Cook Little.....Bar Harbor, Me.
47 Ralph Lowell.....Westwood
36 Dumas Malone.....New York, N. Y.
42 Daniel L. Marsh.....Boston
45 Keyes DeWitt Metcalf.....Belmont
45 Henry Allen Moe.....New York, N. Y.
02 Herbert Putnam.....Washington, D. C.
44 Beardsley Ruml.....New York, N. Y.
34 Erwin Haskell Schell.....Cambridge
38 Charles Seymour.....New Haven, Conn.
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37 Henry Southworth Shaw.....Melrose
48 Alfred Pritchard Sloan, Jr.....New York, N. Y.
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41 Laurence Leathe Winship ..... South Sudbury
48 Henry Merritt Wriston ..... Providence, R. I.
(25) 32 Benjamin Loring Young ..... Weston
39 Owen D. Young ..... New York, N. Y.

CLASS IV—The Humanities—182

Section 1—*Theology, Philosophy, and Psychology*—44

32 Michael Joseph Ahern ..... Weston
32 James Rowland Angell ..... Hamden, Conn.
33 John Gilbert Beebe-Center ..... Swampscott
38 Julius Seelye Bixler ..... Waterville, Me.
46 Brand Blanshard ..... New Haven, Conn.
24 Edwin Garrigues Boring ..... Cambridge
28 Edgar Sheffield Brightman ..... Newton
31 Henry Addington Bruce ..... Cambridge
32 Leonard Carmichael ..... Tufts College
48 Rudolph Carnap ..... Chicago, Ill.
36 Robert Pierce Casey ..... Providence, R. I.
33 Curt John Ducasse ..... Providence, R. I.
43 Angus Dun ..... Washington, D. C.
48 Frederick May Eliot ..... Cambridge
38 James Everett Frame ..... Princeton, N. J.
37 Clarence Henry Graham ..... New York, N. Y.
45 Edwin Ray Guthrie ..... Seattle, Wash.
30 William Henry Paine Hatch ..... Arlington
32 William Healy ..... Natick
35 Clark Leonard Hull ..... New Haven, Conn.
28 Albert Cornelius Knudson ..... Cambridge
32 Karl Spencer Lashley ..... Orange Park, Fla.
29 Clarence Irving Lewis ..... Lexington
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47 Norman Burdett Nash ..... Boston
32 Arthur Darby Nock ..... Cambridge
28 Johnson O'Connor ..... Boston
17 Charles Edwards Park ..... Boston
33 Carroll Cornelius Pratt ..... Princeton, N. J.
48 Hans Reichenbach ..... Los Angeles, Cal.
31 Henry Knox Sherrill ..... New York, N. Y.
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33 Frederic Lyman Wells ..... Newton Highlands
35 Robert Sessions Woodworth ..... New York, N. Y.

CLASS IV, SECTION 2—*History, Archaeology, and Anthropology*—34

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28 James Phinney Baxter, 3d ..... Williamstown
27 Robert Pierpont Blake ..... Cambridge
46 Clarence Saunders Brigham ..... Worcester
(25) 32 William Brooks Cabot ..... Boston
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34 Clarence Gordon Campbell ..... New York, N. Y.
43 Carleton Stevens Coon ..... Cambridge
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38 Claude Moore Fuess ..... Andover
43 Hugh O'Neill Hencken ..... Chestnut Hill
14 Bert Hodge Hill ..... Athens, Greece
27 Earnest Albert Hooton ..... Cambridge
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47 Wilbur Kitchener Jordan ..... Cambridge
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38 Stewart Mitchell ..... Cambridge
15 Samuel Eliot Morison ..... Boston
46 Otto Eduard Neugebauer ..... Providence, R. I.
34 Robert Henry Pfeiffer ..... Cambridge
34 David Moore Robinson ..... University, Miss.
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27 George Sarton ..... Cambridge
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32 Charles Holt Taylor ..... Cambridge
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Dun, A. F, IV: 1
Duncan, J. C. F, I: 1
Dunn, G. F, I: 4
Durand, W. F. F, I: 4
du Vigneaud, see Vigneaud
Eames, A. J. F, II: 2
Edgell, G. H. F, IV: 4
Edgerton, F. F, IV: 3
Edsall, J. T. F, I: 3
Edwards, D. F. F, III: 4
Einaudi, L. FHM, III: 3
Einstein, A. FHM, I: 2
Eliot, F. M. F, IV: 1
Elisséeff, S. F, IV: 3
Ell, C. S. F, III: 4
Emerson, W. F, IV: 4
Emmons, H. W. F, I: 4
Enders, J. F. F, II: 4
Erskine, J. F, IV: 4
Esselen, G. J. F, I: 3
Evans, A. W. F, II: 2
Evans, G. C. F, I: 1
Evans, H. M. F, II: 3
Evans, R. D. F, I: 2
Evans, W. L. FE, I: 3
Ewell, A. W. F, I: 2
Fair, G. M. F, I: 4
Fairchild, F. R. F, III: 3
Farnsworth, H. E. F, I: 2
Faulkner, J. M. F, II: 4
Faull, J. H. FE, II: 2
Fauré-Frémiet, E. FHM, II: 3
Fay, S. B. FE, III: 2
Fenn, W. O. F, II: 3
Ferguson, W. S. FE, IV: 2
Fergusson, S. P. F, II: 1
Fernald, M. L. F, II: 2
Fetter, F. A. F, III: 3
Field, F. T. F, III: 1
Field, W. L. W. F, III: 4
Fieser, L. F. F, I: 3
Finland, M. F, II: 4
Fisher, R. A. FHM, I: 1
Fiske, C. H. F, II: 3
Fitz, R. F, II: 4
Flanders, R. E. F, III: 4
Florin, R. FHM, II: 2
Forbes, A. FE, II: 3
Forbes, E. W. F, IV: 4
Forbes, G. S. FE, I: 3
Forbes, W. C. F, III: 2
Ford, H. S. F, III: 4
Ford, J. D. M. F, IV: 3
Fosdick, R. B. F, III: 4
Frame, J. E. F, IV: 1
Franck, J. FHM, I: 2
Frank, P. F, I: 2
Franklin, P. F, I: 1
Freeman, R. E. F, III: 3
Friedrich, C. J. F, III: 2
Frost, R. F, IV: 4
Fuess, C. M. F, IV: 2
Fuller, L. L. F, III: 1
Fulton, J. F. F, II: 3
Furniss, E. S. F, III: 2
Gamble, J. L. F, II: 4
Gasser, H. S. F, II: 3
Gast, P. R. F, II: 2
Geny, F. FHM, III: 1
Gesell, A. L. F, II: 3
Getting, I. A. F, I: 4
Gibb, H. A. R. FHM, IV: 3
Gibson, R. F, II: 1
Gilboy, G. F, I: 4
Gilliland, E. R. F, I: 4
Gilson, E. FHM, IV: 1
Glueck, S. F, III: 3
Goodale, J. L. F, II: 4
Goodhart, A. L. FHM, III: 1
Goodrich, H. F. F, III: 1
Goodrich, W. F, IV: 4
Goodwin, H. M. F, I: 2
Graham, C. H. F, IV: 1
Graton, L. C. F, II: 1
Gray, F. C. F, III: 4
Gray, L. H. F, IV: 3
Green, T. F. F, III: 1
Greene, Baron. FHM, III: 1
Greene, J. D. F, III: 4
Greene, W. C. F, IV: 3
Gregory, H. E. F, II: 1
Gregory, W. K. F, II: 3

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Grinnell, F. W. F, III: 1
Griswold, E. N. F, III: 1
Gropius, W. F, IV: 4
Gulick, C. B. F, IV: 3
Guthrie, E. R. F, IV: 1
Hadamard, J. S. FHM, I: 1
Haertlein, A. F, I: 4
Haig, R. M. F, III: 3
Haines, C. G. F, III: 2
Hall, J. L. F, III: 1
Ham, T. H. F, II: 4
Hamilton, E. J. F, III: 3
Hand, A. N. F, III: 1
Hand, L. F, III: 1
Hardy, A. C. F, I: 2
Harmon, A. M. F, IV: 3
Harno, A. J. F, III: 1
Harris, L. F, I: 3
Harris, S. E. F, III: 3
Harrison, G. R. F, I: 2
Harrison, R. G. F, II: 4
Harvey, E. N. F, II: 3
Hastings, A. B. F, I: 3
Hatch, W. H. P. F, IV: 1
Havens, R. D. F, IV: 3
Hawkins, R. L. FE, IV: 3
Hawtrey, R. G. FHM, III: 3
Hayes, B. H., Jr. F, IV: 4
Hazen, H. L. F, I: 4
Healy, W. F, IV: 1
Hencken, H. O. F, IV: 2
Hendrickson, G. L. F, IV: 3
Hertzsprung, E. FHM, I: 1
Heyrovsky, J. FHM, I: 3
Hill, A. V. FHM, II: 3
Hill, B. H. F, IV: 2
Hill, E. B. FE, IV: 4
Hille, E. F, I: 1
Hillyer, R. S. F, IV: 4
Hindemith, P. FHM, IV: 4
Hippel, A. R., von F, I: 4
Hisaw, F. L. F, II: 3
Hitchcock, F. L. FE, I: 1
Hoadley, L. F, II: 3
Hoagland, D. R. F, II: 2
Hoagland, H. F, II: 3
Hockett, R. C. F, I: 3
Hocking, W. E. FE, IV: 1
Holborn, H. F, III: 2
Holcombe, A. N. F, III: 2
Holmes, A. FHM, II: 1
Holmes, E. J. F, III: 4
Holmes, H. W. FE, III: 3
Holmes, S. J. F, II: 3
Hooker, S. B. F, II: 4
Hooton, E. A. F, IV: 2
Hopkins, E. M. F, III: 4
Hopkinson, C. F, IV: 4
Horwood, M. P. F, I: 4
Hoskins, H. L. F, IV: 2
Hoskins, R. G. F, II: 3
Hottel, H. C. F, I: 4
Houssay, B. A. FHM, II: 3
Hovgaard, W. FE, I: 4
Howard, L. O. F, II: 3
Howard, W. G. F, IV: 3
Howe, C. D. FHM, I: 4
Howe, M. A. DeW. F, IV: 4
Howe, M. DeW. F, III: 1
Howe, P. R. F, II: 4
Hu Shih. FHM, III: 2
Hubbard, J. C. F, I: 2
Hudnut, J. F, IV: 4
Hull, C. L. F, IV: 1
Hull, G. F. F, I: 2
Hume, E. E. F, II: 4
Humphreys, W. J. F, II: 1
Hunsaker, J. C. F, I: 4
Hunt, B. C. F, III: 3
Hunt, F. V. F, I: 2
Huntington, A. M. F, IV: 4
Huntington, E. V. F, I: 1
Huntress, E. H. F, I: 3
Huntsman, A. G. FHM, II: 3
Hurlbut, C. S., Jr. F, II: 1
Imms, A. D. FHM, II: 3
Iselin, C. O. F, II: 1
Jack, J. G. F, II: 2
Jack, J. R. F, I: 4
Jackson, D. C. F, I: 4
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Jackson, W. A. F, IV: 4
Jaeger, W. W. F, IV: 3

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Jessup, P. C. F, III: 2
Jewett, F. B. F, I: 4
Joffé, A. F. FHM, I: 2
Johnson, L. J. F, I: 4
Johnson, M. M. F, III: 1
Johnston, I. M. F, II: 2
Jones, D. F. F, II: 2
Jones, H. M. F, IV: 4
Jones, Sir H. S. FHM, I: 1
Jordan, W. K. F, IV: 2
Joslin, E. P. F, II: 4
Kärmän, T., von F, I: 4
Keefer, C. S. F, II: 4
Keenan, J. H. F, I: 4
Keith, Sir A. FHM, II: 4
Keller, C. T. F, III: 4
Kelsen, H. FHM, III: 1
Kemble, E. C. F, I: 2
Kendall, H. P. F, III: 4
Keniston, H. F, IV: 3
Kent, R. G. F, IV: 3
Keyes, F. G. F, I: 3
Killian, J. R., Jr. F, III: 4
Kinkeldey, O. F, IV: 4
King, R. W. P. F, I: 2
Kistiakowsky, G. B. F, I: 3
Klausner, J. FHM, IV: 3
Kluckhohn, C. K. M. F, IV: 2
Knight, F. H. F, III: 3
Knopf, A. F, II: 1
Knudson, A. C. F, IV: 1
Köhler, W. FHM, IV: 1
Koussevitzky, S. FHM, IV: 4
Kraus, C. A. F, I: 3
Kretschmer, P. FHM, IV: 3
Kroeber, A. L. F, IV: 2
Krogh, A. FHM, II: 3
Kurath, H. F, IV: 3
Lamb, A. B. F, I: 3
Lampland, C. O. F, I: 1
Lancaster, H. C. F, IV: 3
Land, E. H. F, I: 2
Landis, E. M. F, II: 3
Landis, J. M. F, III: 1
Langley, E. F. FE, IV: 3
Langmuir, I. F, I: 3
Lansing, A. F, IV: 2
La Piana, G. FE, IV: 2
Lapicque, L. E. FHM, II: 3
Larsen, E. S., Jr. F, II: 1
Lashley, K. S. F, IV: 1
Laue, M., von FHM, I: 2
Lawrence, E. O. F, I: 2
Lawrence, R. R. F, I: 4
Lawrence, W. H. F, I: 4
Lawson, A. C. F, II: 1
Lee, R. I. F, II: 4
Leeds, M. E. F, III: 4
Leith, C. K. F, II: 1
Leland, W. G. F, IV: 2
Lessells, J. M. F, I: 4
Levine, S. A. F, II: 4
Levinson, N. F, I: 1
Lewis, C. I. F, IV: 1
Lewis, F. T. F, II: 3
Lewis, W. K. F, I: 3
Lilienthal, D. E. F, III: 4
Lillie, R. S. F, II: 3
Lindblad, B. FHM, I: 1
Lindsay, R. B. F, I: 2
Linforth, I. M. F, IV: 3
Lingelbach, W. E. F, IV: 2
Little, C. C. F, III: 4
Locke, E. A. F, II: 4
Lombardi, L. FHM, I: 4
Longcope, W. T. F, II: 4
Loofbourow, J. R. F, II: 3
Lord, M. E. F, IV: 4
Lowe, E. A. F, IV: 3
Lowell, R. F, III: 4
Lull, R. S. F, II: 3
Lund, F. B. F, II: 4
Lutz, B. R. F, II: 3
Luyten, W. J. F, I: 1
Lyman, T. F, I: 2
McAdams, W. H. F, I: 4
McCrea, R. C. F, III: 3
McEwen, G. F. F, II: 1
MacGregor, C. W. F, I: 4
McIlwain, C. H. FE, IV: 2
MacInnes, D. A. F, I: 3

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McKeon, R. P. F, IV: 1
MacLane, S. F, I: 1
McLaren, W. W. F, III: 3
McLaughlin, D. H. F, II: 1
Maclaurin, W. R. F, III: 3
Macmillan, Lord. FHM, III: 1
McNair, M. P. F, III: 3
Macneil, S. F, III: 1
MacNider, W. de B. F, II: 4
Maginnis, C. D. F, IV: 4
Magruder, C. F, III: 1
Maheshwari, P. FHM, II: 2
Makarewicz, J. FHM, III: 1
Malamud, W. F, II: 4
Malone, D. F, III: 4
Mangelsdorf, P. C. F, II: 2
Manship, P. F, IV: 4
Margerie, E., de FHM, II: 1
Marin, J. F, IV: 4
Mark, K. L. F, I: 3
Marks, L. S. F, I: 4
Marsh, D. L. F, III: 4
Marshall, L. C. F, III: 3
Martin, W. T. F, I: 1
Mason, D. G. F, IV: 4
Mather, F. J. F, IV: 4
Mather, K. F. F, II: 1
Maunier, R. FHM, III: 3
Mayo, E. FE, III: 3
Mazon, P. FHM, IV: 3
Mead, M. F, IV: 2
Mead, W. J. F, II: 1
Mees, C. E. K. F, I: 3
Meinecke, F. FHM, IV: 2
Melander, A. L. F, II: 3
Menéndez Pidal, R. FHM, IV: 3
Menzel, D. H. F, I: 1
Meriam, R. S. F, III: 3
Meritt, B. D. F, IV: 3
Merriam, C. E. F, III: 2
Merrill, E. D. FE, II: 2
Metcalf, K. DeW. F, III: 4
Meyer, K. F. F, II: 3
Milas, N. A. F, I: 3
Miller, G. A. F, I: 1
Miller, G. S. F, II: 3
Miller, W. J. F, II: 1
Millikan, R. A. F, I: 2
Mills, F. C. F, III: 3
Milne, E. A. FHM, I: 1
Mimno, H. R. F, I: 2
Miner, L. M. S. F, II: 4
Minot, G. R. F, II: 4
Mises, R., von F, I: 4
Mitchell, S. F, IV: 2
Mitchell, S. A. F, I: 1
Mitchell, W. DeW. F, III: 1
Miyabe, K. FHM, II: 2
Miyajima, M. FHM, II: 4
Moe, H. A. F, III: 4
Monroe, A. E. F, III: 3
Morandière, L. J., de la FHM, III: 1
Moreland, E. L. F, I: 4
Morey, C. R. F, IV: 4
Morgan, E. M. F, III: 1
Morison, S. E. F, IV: 2
Morris, F. K. F, II: 1
Morse, M. F, I: 1
Morse, P. M. F, I: 2
Morton, A. A. F, I: 3
Moss, W. L. F, II: 4
Moulton, F. R. F, I: 1
Mueller, E. F, I: 3
Mueller, J. H. F, II: 4
Muller, H. J. F, II: 3
Mumford, L. F, IV: 4
Munro, T. F, IV: 4
Munro, W. B. F, III: 2
Murdock, K. B. F, IV: 4
Murphy, A. E. F, IV: 1
Murray, G. FHM, IV: 4
Murray, H. A., Jr. F, IV: 1
Nash, N. B. F, IV: 1
Navarro, T. FHM, IV: 3
Neugebauer, O. E. F, IV: 2
Neumann, J., von F, I: 1
Newhouse, W. H. F, II: 1
Nilsson, M. P. FHM, IV: 2
Nitze, W. A. F, IV: 3
Nock, A. D. F, IV: 1
Nourse, E. G. F, III: 3
Noyes, G. R. F, IV: 3

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Noyes, W. A., Jr. F, I: 3
O'Brian, J. L. F, III: 1
O'Connor, J. F, IV: 1
Oertel, H. FHM, IV: 3
Ogburn, W. F. F, III: 3
Oldenberg, O. F, I: 2
Olmsted, F. L. F, I: 4
Oncley, J. L. F, I: 3
Oort, J. H. FHM, I: 1
Oppenheimer, J. R. F, I: 2
Ordoñez, E. FHM, II: 1
Osgood, R. B. FE, II: 4
Osterhout, W. J. V. F, II: 2
Page, L. F, I: 2
Palache, C. FE, II: 1
Palacios, A. L. FHM, III: 4
Palmer, W. W. F, II: 4
Paneth, F. FHM, I: 3
Panofsky, E. F, IV: 4
Park, C. E. F, IV: 1
Parker, G. H. F, II: 3
Parkman, H., Jr. F, III: 1
Parodi, L. R. FHM, II: 2
Parsons, T. F, III: 3
Patch, H. R. F, IV: 3
Paton, W. A. F, III: 3
Pauling, L. C. F, I: 3
Payne-Gaposchkin, C. F, I: 1
Pearse, L. F, I: 4
Pease, A. S. F, IV: 3
Peers, E. A. FHM, IV: 4
Peirce, G. J. F, II: 2
Pender, H. F, I: 4
Pepper, G. W. F, III: 1
Peters, J. L. F, II: 3
Pfeiffer, R. H. F, IV: 2
Phillips, H. B. F, I: 1
Phillips, W. F, III: 2
Philpott, A. J. F, IV: 4
Pickard, G. W. F, I: 4
Pierce, G. W. F, I: 2
Piéron, H. FHM, IV: 1
Pigou, A. C. FHM, III: 3
Pilsbry, H. A. F, II: 3
Pincus, G. F, II: 3
Piston, W. H. F, IV: 4
Poor, C. L. F, I: 1
Porsild, A. E. FHM, II: 2
Post, C. R. F, IV: 4
Pound, R. F, III: 1
Prandtl, L. FHM, I: 4
Pratt, C. C. F, IV: 1
Pratt, F. H. F, II: 3
Pratt, J. H. F, II: 4
Prescott, S. C. FE, I: 3
Probst, E. FHM, I: 4
Purves, C. B. F, I: 3
Putnam, H. F, III: 4
Putnam, T. J. F, II: 4
Qua, S. E. F, III: 1
Quinby, W. C. F, II: 4
Rabaud, H. FHM, IV: 4
Rabi, I. I. F, I: 2
Rackemann, F. M. F, II: 4
Rand, H. W. F, II: 3
Rapport, D. F, II: 3
Raup, H. M. F, II: 2
Raymond, P. E. FE, II: 1
Redfield, A. C. F, II: 3
Rehder, A. F, II: 2
Reichenbach, H. F, IV: 1
Renner, O. FHM, II: 2
Richards, A. N. F, II: 3
Richardson, R. G. D. F, I: 1
Riddle, O. F, II: 3
Rist, C. FHM, III: 3
Robbins, W. J. F, II: 2
Robertson, D. H. FHM, III: 3
Robinson, D. M. F, IV: 2
Robinson, F. N. F, IV: 3
Robinson, Sir R. FHM, I: 3
Rock, J. F, II: 4
Roeder, K. D. F, II: 3
Roethlisberger, F. J. F, III: 3
Rogers, A. F. F, II: 1
Rollins, H. E. F, IV: 3
Romer, A. S. F, II: 3
Romero, F. FHM, IV: 1
Root, R. K. F, IV: 3
Rosanoff, M. A. F, I: 3
Rossby, C. G. A. F, II: 1
Rossi, B. B. F, I: 2
Rostovtzeff, M. I. F, IV: 2
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Ruml, B. F, III: 4
Russell, F. F. F, II: 4
Russell, G. E. FE, I: 4
Russell, H. N. F, I: 1
Ruthven, A. G. F, II: 3
Ruzicka, L. FHM, I: 3
Sachs, P. J. F, IV: 4
Saha, M. N. FHM, I: 1
Sahni, B. FHM, II: 2
Salter, W. T. F, II: 4
Salvemini, G. F, III: 2
Samuelson, P. A. F, III: 3
Sanders, H. A. F, IV: 3
Sanders, T. H. F, III: 3
Sarton, G. F, IV: 2
Sayre, F. B. F, III: 1
Scatchard, G. F, I: 3
Schaller, W. T. F, II: 1
Schell, E. H. F, III: 4
Schmitt, B. E. F, IV: 2
Schmitt, F. O. F, II: 3
Scholte, J. H. FHM, IV: 4
Schumb, W. C. F, I: 3
Schumpeter, J. A. F, III: 3
Schwinger, J. S. F, I: 2
Scott, A. W. F, III: 1
Scott, D. F, IV: 2
Sedgwick, E. F, IV: 4
Sedgwick, H. D. F, IV: 4
Selekman, B. M. F, III: 3
Seymour, C. F, III: 4
Seznec, J. J. F, IV: 3
Shajn, G. A. FHM, I: 1
Shapley, H. F, I: 1
Shattuck, G. C. F, II: 4
Shattuck, H. L. F, III: 4
Shaw, H. S. F, III: 4
Sherburn, G. W. F, IV: 3
Sherrill, H. K. F, IV: 1
Sherrill, M. S. F, I: 3
Sherrington, Sir C. S. FHM, II: 4
Sherwood, T. K. F, I: 4
Shimer, H. W. FE, II: 1
Sibelius, J. J. C. FHM, IV: 4
Sidgwick, N. V. FHM, I: 3
Simmons, J. S. F, II: 4
Simonds, B. F, IV: 4
Simpson, G. G. F, II: 1
Simpson, S. P. F, III: 1
Sinnott, E. W. F, II. 2
Slater, J. C. F, I: 2
Slipher, V. M. F, I: 1
Sloan, A. P., Jr. F, III: 4
Sloan, J. F, IV: 4
Smith, A. C. F, II: 2
Smith, D. S. F, IV: 4
Smith, G. M. F, II: 2
Smith, H. M. F, I: 3
Smith, L. B. F, I: 3
Smith, P. F, III: 4
Smith, R. M. F, II: 4
Smith, Sir W. W. FHM, II: 2
Snyder, V. F, I: 1
Soderberg, R. C. F, I: 4
Sollmann, T. H. F, II: 4
Sommerfeld, A. FHM, I: 2
Sorokin, P. A. F, III: 3
Sosman, M. C. F, II: 4
Spalding, W. R. FE, IV: 4
Spaulding, F. T. F, III: 3
Spaulding, H. N. F, III: 4
Sperry, W. L. F, IV: 1
Spinden, H. J. F, IV: 2
Spoehr, H. A. F, II: 2
Spofford, C. M. F, I: 4
Sprague, O. M. W. F, III: 3
Stafford, R. H. F, IV: 1
Stakman, E. C. F, II: 2
Starck, T. F, IV: 3
Stearns, A. W. F, III: 4
Stebbins, J. F, I: 1
Stephenson, C. C. F, I: 3
Stetson, H. C. F, II: 1
Stetson, H. T. F, I: 1
Stevens, S. S. F, IV: 1
Stewart, G. W. F, I: 2
Stewart, R. B. F, III: 2
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Street, J. C. F, I: 2
Struik, D. J. F, I: 1
Struve, O. F, I: 1
Svedberg, T. FHM, I: 3
Sverdrup, H. U. F, II: 1
Swan, T. W. F, III: 1
Takayanagi, K. FHM, III: 2
Talbot, F. B. FE, II: 4
Tarski, A. F, IV: 1
Taylor, C. H. F, IV: 2
Taylor, C. L., Jr. F, IV: 1
Taylor, F. H. F, IV: 4
Taylor, H. S. F, I: 3
Taylor, W. R. F, II: 2
Terman, F. E. F, I: 4
Terman, L. M. F, IV: 1
Terzaghi, K. F, I: 4
Thannhauser, S. J. F, II: 4
Thimann, K. V. F, II: 2
Thomas, F. W. FHM, IV: 3
Thompson, M. deK. F, I: 2
Thompson, R. F, IV: 4
Thomson, G. H. FHM, IV: 1
Thomson, Sir G. P. FHM, I: 2
Thomson, W. F, IV: 3
Thorn, G. W. F, II: 4
Thorndike, E. L. F, IV: 1
Thurstone, L. L. F, IV: 1
Torrey, C. C. F, IV: 3
Tosdal, H. R. F, III: 3
Tozzer, A. M. F, IV: 2
Trevelyan, G. M. FHM, IV: 2
Tucker, D. S. F, III: 3
Turner, C. E. FE, III: 4
Twaddell, W. F. F, IV: 3
Tyzzer, E. E. F, II: 4
Ulich, R. F, III: 3
Ullman, B. L. F, IV: 3
Urey, H. C. F, I: 3
Usher, A. P. F, III: 3
Vallarta, M. S. F, I: 2
Vallée Poussin, C. J., de la FHM, I: 1
Van de Graaff, R. J. F, I: 2
Van Hook, L. R. FE, IV: 3
Van Vleck, J. H. F, I: 2
Vaughan, T. W. F, II: 1
Veblen, O. F, I: 1
Vecchio, G., Del FHM, III: 1
Verhoeff, F. H. F, II: 4
Vickery, H. B. F, II: 3
Viëtor, K. F, IV: 4
Viets, H. R. F, IV: 2
Vigneaud, V., du F, I: 3
Vincent, J. H. FHM, II: 4
Viner, J. F, III: 3
von Hippel, see Hippel
von Kármán, see Kármán
von Laue, see Laue
von Mises, see Mises
von Neumann, see Neumann
Wagner, K. W. FHM, I: 4
Wagner, M. F, IV: 4
Wald, G. F, II: 3
Walsh, J. L. F, I: 1
Wambaugh, S. F, III: 2
Warner, E. P. F, I: 4
Warren, B. E. F, I: 2
Warren, C. H. F, II: 1
Warren, S. F, II: 4
Washburn, H. B. FE, IV: 1
Watson, J. B. F, IV: 1
Wearn, J. T. F, II: 4
Weatherby, C. A. F, II: 2
Webster, D. L. F, I: 2
Webster, E. S. F, III: 4
Weeks, E. A., Jr. F, IV: 4
Weiser, H. B. F, I: 3
Weisskopf, V. F. F, I: 2
Welles, S. F, III: 2
Wells, F. L. F, IV: 1
Welsh, J. H., Jr. F, II: 3
Went, F. W. F, II: 2
Westergaard, H. M. F, I: 4
Weston, G. B. FE, IV: 3
Weston, K. E. F, IV: 4
Weston, W. H., Jr. F, II: 2
Wetmore, R. H. F, II: 2
Weyl, H. FHM, I: 1
Weysse, A. W. F, II: 3
Whipple, F. L. F, I: 1
White, P. D. F, II: 4
Whitehead, T. N. F, III: 3

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Whitman, E. A. FE, III: 1
Whitman, W. G. F, I: 4
Whitney, W. R. F, I: 3
Whittlesey, D. S. F, II: 1
Widder, D. V. F, I: 1
Wieland, H. FHM, I: 3
Wilbur, J. B. F, I: 4
Wild, P. S., Jr. F, III: 2
Wilkins, E. H. F, IV: 3
Williams, J. H. F, III: 3
Williams, R. S. F, I: 3
Willis, B. F, II: 1
Willits, J. H. F, III: 3
Willoughby, W. F. F, III: 2
Wilson, C. E. F, III: 4
Wilson, E. B. F, I: 2
Wilson, E. B., Jr. F, I: 3
Wilson, G. G. F, III: 2
Wilson, H. E. F, III: 2
Winlock, H. E. F, IV: 4
Winship, L. L. F, III: 4
Wislocki, G. B. F, II: 3
Wolbach, S. B. F, II: 4
Wolfson, H. A. F, IV: 3
Wolman, L. F, III: 3
Wong, Wen-hao. FHM, II: 1
Wood, R. W. F, I: 2
Woods, F. S. FE, I: 1
Woodward, R. B. F, I: 3
Woodworth, R. S. F, IV: 1
Worrell, W. H. FE, IV: 3
Wright, Lord. FHM, III: 1
Wright, C. H. C. FE, IV: 4
Wright, F. E. F, II: 1
Wright, Q. F, III: 2
Wright, S. F, II: 3
Wriston, H. M. F, III: 4
Wu, J. C. H. FHM, III: 1
Wulff, J. F, I: 4
Wurster, W. W. F, IV: 4
Wyman, J., Jr. F, II: 3
Wyman, L. C. F, II: 3
Wyzanski, C. E., Jr. F, III: 1
Yeomans, H. A. F, III: 2
Yerkes, R. M. F, II: 3
Young, B. L. F, III: 4
Young, O. D. F, III: 4
Young, R. C. F, I: 3
Zariski, O. F, I: 1
Zeleny, J. F, I: 2
Zimmerman, C. C. F, III: 3
Zworykin, V. K. F, I: 4

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STATUTES

The American Academy of Arts and Sciences

Adopted November 8, 1911: *amended* May 8, 1912, *January* 8, *and May* 14, 1913, *April* 14, 1915, *April* 12, 1916, *April* 10, 1918, *May* 14, 1919, *February* 8, *April* 12, *and December* 13, 1922, *February* 14, *March* 14, *and October* 10, 1923, *March* 10, 1926, *May* 9, 1928, *April* 8, *and November* 11, 1931, *April* 12, 1933, *February* 14, 1934, *December* 14, 1938, *January* 11, *April* 12, 1939, *May* 8, 1940, *May* 14, 1941, *November* 18, 1942, *and January* 12, 1944, *May* 9, 1945, *November* 14, 1945, *February* 2, 1946, *October* 9, 1946, *and October* 8, 1947.

CHAPTER I

The Academy and Its Corporate Seal

Article 1. The American Academy of Arts and Sciences is a body politic and corporate by the same name, forever, established by the Council and House of Representatives in General Court of the Province of Massachusetts Bay as recorded in Chap. 46 of the Acts of 1779.

Article 2. As enacted above, the stated end and design of the institution of the said academy is to promote and encourage the knowledge of the antiquities of America, and of the natural history of the country, and to determine the uses to which the various natural productions of the country may be applied; to promote and encourage medical discoveries, mathematical disquisitions, philosophical enquiries and experiments, astronomical, meteorological and geographical observations; and improvements in agriculture, arts, manufacture and commerce; and, in fine, to cultivate every art and science which may tend to advance the interest, honor, dignity and happiness of a free, independent and virtuous people.

Article 3. The Corporate Seal of the Academy shall be as here depicted.

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ARTICLE 4. The Secretary shall have the custody of the Corporate Seal.

See Chap. v, art. 3; chap. vi, art. 1.

CHAPTER II

MEMBERSHIP AND DUES

ARTICLE 1. The Academy shall consist of Fellows, elected from the citizens or residents of the United States of America, Fellows Emeriti, and Foreign Honorary Members. They are arranged in four Classes, according to the Arts and Sciences in which they are severally proficient, and each Class shall be divided into four Sections, namely:

CLASS I. *The Mathematical and Physical Sciences*
- Section 1. Mathematics and Astronomy
- Section 2. Physics
- Section 3. Chemistry
- Section 4. Technology and Engineering

CLASS II. *The Natural and Physiological Sciences*
- Section 1. Geology, Mineralogy, and Physics of the Globe
- Section 2. Botany
- Section 3. Zoology and Physiology
- Section 4. Medicine and Surgery

CLASS III. *The Social Arts*
- Section 1. Jurisprudence
- Section 2. Government, International Law, and Diplomacy
- Section 3. Economics and Sociology
- Section 4. Administration and Affairs

CLASS IV. *The Humanities*
- Section 1. Theology, Philosophy, and Psychology
- Section 2. History, Archaeology, and Anthropology
- Section 3. Philology
- Section 4. The Fine Arts and Belles Lettres

ARTICLE 2. The number of Fellows shall not exceed One thousand, of whom not more then Eight hundred shall be residents of Massachusetts, nor shall there be more than Two hundred and seventy-five in any one Class.

Any Fellow of the Academy on retiring from his academic or other regular duties may, if he so requests in writing, and with the approval of the Council, be transferred to the status of Fellow Emeritus.

Fellows Emeriti shall be exempt from payment of dues. They may not hold elective office in the Academy, nor serve on Standing Com-

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mittees, nor vote at meetings, but shall have all the other privileges of Fellowship.

Fellows Emeriti shall be separately classified and shall be outside the statutory limit set on the total number of Fellows and the number in a given Class.

See Chap. ix, art. 3; chap. x, art. 1.

ARTICLE 3. The number of Foreign Honorary Members shall not exceed One hundred and fifty. They shall be chosen from citizens of foreign countries most eminent for their discoveries and attainments in any of the Classes above enumerated. There shall be not more than Forty-five in any one Class.

ARTICLE 4. Diplomas signed by the President and the Vice-President of the Class to which the member belongs, and countersigned by the Secretary, shall be given to Fellows and Foreign Honorary Members.

ARTICLE 5. If any person, after being notified of his election as Fellow or Foreign Honorary Member, shall neglect for six months to accept in writing, his election shall be void.

ARTICLE 6. Every Fellow resident within fifty miles of Boston hereafter elected shall pay an Admission Fee of Ten dollars: if he shall neglect to pay this Fee within six months of the date of his election, his election shall become void.

Every Fellow resident within fifty miles of Boston shall pay such Annual Dues, not exceeding Fifteen dollars, as shall be voted by the Academy at each Annual Meeting, at which time they shall become due.

Every Fellow residing more than fifty miles from Boston elected after 1938 shall pay, and other non-resident Fellows may pay, Annual Dues equal to one-half the amount set for resident Fellows at each Annual Meeting and due on the same date.

Any Fellow shall be exempt from further payment of Annual Dues who has paid such dues for forty years, or having attained the age of seventy-five, has paid dues for twenty-five years.

Any Fellow may also be exempt from further payment of annual dues upon payment into the treasury of the Academy the sum of Two hundred dollars in addition to his previous payments.

Any Fellow not previously subject to Annual Dues who takes up his residence within fifty miles of Boston, shall pay to the Treasurer, within three months thereafter, Annual Dues for the current year, and if he shall neglect to make this payment within the specified time,

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after having been notified by the Treasurer of the requirements of this Article of the Statutes, he shall cease to be a Fellow.

ARTICLE 7. Any Fellow, resident or non-resident, who shall neglect to pay his Annual Dues for six months after they are due and who ignores notification by the Treasurer of the requirements of this Article of the Statutes shall cease to be a Fellow.

ARTICLE 8. Only Fellows who pay Annual Dues or have commuted them may hold elective office in the Academy or serve on Standing Committees or vote at meetings.

ARTICLE 9. Upon petition of any Fellow, the Council may by a majority vote suspend the application of any penalties hereinabove prescribed in this chapter for an additional period of time not longer than three months.

ARTICLE 10. If, in the opinion of a majority of the entire Council, any Fellow or Foreign Honorary Member shall have rendered himself unworthy of a place in the Academy, the Council shall recommend to the Academy the termination of his membership; and if three-fourths of the Fellows present out of a total attendance of not less than fifty at a Stated Meeting, or at a Special Meeting called for the purpose, shall adopt this recommendation, his name shall be stricken from the Roll.

See Chap. iii; chap. vi, art. 5 and 6; chap. x, art. 1.

CHAPTER III

NOMINATION AND ELECTION OF FELLOWS AND FOREIGN HONORARY MEMBERS

The procedure for nomination and election of Fellows and Foreign Honorary Members shall be as follows:

ARTICLE 1. Nominations may be made at any time by any two Fellows in writing on forms to be provided by the Secretary and shall be referred by him to the Committee on Membership.

The Committee on Membership shall meet following the stated meetings of the Academy in May, November, February and March, and at such other times as it may determine, to appraise nominations received by it from the Fellows from time to time, to originate further nominations, and to approve as candidates for election those receiving the favorable vote of two-thirds of the Committee members present in any meeting attended by not less than five of its members.

Immediately following its meeting in February, the Committee shall cause to be sent to every Fellow a list of nominees, with biographical

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and professional data thereon, together with names of nominators, for appraisal, expression of preference, or other comment by the Fellows.

The Committee, at its March meeting, shall review all nominations, together with comments by the Fellows thereon, and shall compile a list of approved candidates for the annual election of Fellows and Foreign Honorary Members. It shall present this list together with data pertaining thereto to the Council not later than at the Stated Meeting of the Council in April.

The Council, by vote of the majority of members present at a meeting, shall make final nominations from the list of approved persons recommended by the Committee on Membership for election by the Fellows.

ARTICLE 2. Election of Fellows and Foreign Honorary Members shall be made by a majority of the Fellows present at the Annual Meeting in May, from the nominations presented at that meeting by the Council.

ARTICLE 3. Each Fellow or Foreign Honorary Member shall be notified in writing by the Secretary immediately following his election.

See Chap. ii; chap. vi, art. 5; chap. x, art. 1; chap. xi, art. 1 (ii).

CHAPTER IV

OFFICERS

ARTICLE 1. The Officers of the Academy shall be a President (who shall be Chairman of the Council), four Vice-Presidents (one from each Class), a Secretary (who shall be Secretary of the Council), a Treasurer, a Librarian, and an Editor, all of whom shall be elected by ballot at the Annual Meeting, and shall take office at the close of that meeting, and shall hold their respective offices for one year, and until others are duly chosen and take office.

There shall be also sixteen Councillors, one from each Section of each Class. At each Annual Meeting four Councillors, one from each Class, shall be elected by ballot to serve for a term of four years, and they shall take office at the close of that meeting, and shall hold office until others are duly chosen and take office. The same Fellows shall not be eligible for two successive terms.

The Councillors, with the officers previously named, and the Chairmen of the Standing Committees, *ex officiis*, shall constitute the Council.

See Chap. xi, art. 1.

ARTICLE 2. If any officer be unable, through death, absence, or disability, to fulfill the duties of his office, or if he shall resign, his

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place may be filled by the Council in its discretion for any part or the whole of the unexpired term.

ARTICLE 3. At the Stated Meeting in March, the President shall appoint a Nominating Committee of four Fellows having the right to vote, one from each Class. This Committee shall prepare a list of nominees for the several offices to be filled, and for the Standing Committees, and file it with the Secretary not later than four weeks before the Annual Meeting.

ARTICLE 4. Independent nominations for any office, if signed by at least twenty Fellows having the right to vote, and received by the Secretary not less than ten days before the Annual Meeting, shall be included in the election procedure.

ARTICLE 5. The Secretary shall prepare for use in voting at the Annual Meeting a ballot containing the names of all persons duly nominated for office.

CHAPTER V

THE PRESIDENT

ARTICLE 1. The President, or in his absence a Vice-President, shall preside at meetings of the Academy.

See Chap. vi, art. 3.

ARTICLE 2. The President shall be the chief executive officer of the Academy. He shall present to the Council for its consideration all matters pertinent to the interests of the Academy and to the discharge of its obligations to the community or to the advancement of scholarship.

ARTICLE 3. Any deed or writing to which the Corporate Seal is to be affixed, except leases of real estate, shall be executed in the name of the Academy by the President or in the event of his death, absence, or inability, by one of the Vice-Presidents, when thereto duly authorized by the Council.

ARTICLE 4. In case of incapacity of the President, the Council shall designate a Vice-President to carry out the duties of the office.

See Chap. ii, art. 4; chap. iv, art. 1, 3; chap. vi, art. 3; chap. viii, art. 4; chap. x, art. 3; chap. xi, art. 1 (ii), (iii), (x); chap. xii, art. 1.

CHAPTER VI

THE SECRETARY

ARTICLE 1. The Secretary shall provide for the custody of the

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Charter, Corporate Seal, Statute Book, Journals of the Academy, and other Archives.

ARTICLE 2. He shall be responsible for the correspondence of the Academy and of the Council. At each meeting of the Council he shall present any important communications addressed to the Academy which have been received since the previous meeting, and at the next meeting of the Academy he shall present such matters as the Council may determine.

ARTICLE 3. He shall attend the meetings of the Academy and the Council and shall arrange for the keeping of a faithful record of the attendance and of the proceedings. In the absence of the President and of all the Vice-Presidents, he shall call the meeting to order and preside until a chairman is chosen by majority vote of the Fellows present.

ARTICLE 4. He shall apprise officers and committees of their election or appointment, and inform the Treasurer and the Chairman of each Standing Committee of appropriations of money voted by the Academy.

ARTICLE 5. He shall notify all persons who may be elected Fellows or Foreign Honorary Members, send to each a copy of the Statutes, and on their acceptance issue the proper Diploma. After all elections, he shall insert in the Records the names of the Fellows by whom the successful nominees were proposed.

ARTICLE 6. He shall keep and cause to be printed annually a list of the Fellows and Foreign Honorary Members, arranged in their several Classes and Sections, and a list of Fellows and Foreign Honorary Members of whose deaths he has been informed.

ARTICLE 7. He shall arrange for the preservation of records of the death of Fellows and Foreign Honorary Members and biographical notices published on the occasion of their death, or at other times.

See Chap. i, art. 2; chap. ii, art. 4; chap. iii; chap. iv, art. 1, 3, 4, 5; chap. ix, art. 3; chap. xi, art. 1 (iii), 2; chap. xii, art. 1, 3.

CHAPTER VII

THE TREASURER AND THE TREASURY

ARTICLE 1. The Treasurer shall collect all money due or payable to the Academy and all gifts or bequests made to it. He shall pay all bills due and payable by the Academy when approved by the proper officers. He shall sign all leases of real estate in the name of the Academy. He shall be the official custodian of all bonds, stocks and other securities and, with the written approval of any one member of

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the Committee on Finance, he shall have full authority to sell and transfer, invest and reinvest from time to time in such manner and upon such terms as shall to him seem best, the whole or any part of the personal property of the said Academy.

He shall keep a faithful account of all receipts and expenditures, submit his accounts annually to the Auditing Committee, and render them at the expiration of his term of office, or whenever required to do so by the Academy or the Council.

He shall keep separate accounts of the income of the Rumford Fund, and of all other special Funds, and of the appropriation thereof, and render them annually.

He shall fund all payments received in commutation of Dues, their income only, to be applied toward current expenditures.

His accounts shall always be open to the inspection of the Council.

ARTICLE 2. He shall report annually to the Council at its March meeting on the expected income of the various Funds and from all other sources, together with appropriations needed by Officers and Standing Committees for the ensuing fiscal year. He shall also report the names of all Fellows who may be then delinquent in the payment of their Annual Dues.

ARTICLE 3. He shall give such security for the trust reposed in him as the Academy may require.

ARTICLE 4. With the approval of a majority of the Committee on Finance, he may appoint an Assistant Treasurer to perform his duties, for whose acts, as such assistant, he shall be responsible; or, with like approval and responsibility, he may employ any Trust Company doing business in Boston as his agent for the same purpose, the compensation of such Assistant Treasurer or agent to be fixed by the Committee on Finance and paid from the Funds of the Academy.

ARTICLE 5. At the Annual Meeting he shall report in print all his official doings for the preceding year, stating the amount and condition of all the property of the Academy entrusted to him, and the character of the investments.

ARTICLE 6. The Financial Year of the Academy shall begin with the first day of April.

ARTICLE 7. No person or committee shall incur any debt or liability in the name of the Academy, unless in accordance with a previous vote and appropriation therefor by the Academy or the Council, or sell or otherwise dispose of any property of the Academy,

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except cash or invested funds, without previous consent and approval of the Council.

See Chap. ii, art. 2, 6, 7, 8; chap. iv, art. 1; chap. vi, art. 4; chap. ix, art. 6; chap. xi, art. 1 (i), (iv), (v), art. 2; chap. xii, art. 1.

CHAPTER VIII

The Librarian and the Library

Article 1. The Librarian shall have charge of the Library and keep a correct catalog of it.

Article 2. The Librarian shall have authority to expend such sums as may be appropriated by the Academy for the purchase, repair, or maintenance of books, periodicals, etc., and for defraying other necessary expenses connected with the Library.

Article 3. All books procured from the income of the Rumford Fund or other special funds shall contain a bookplate expressing the fact.

Article 4. The Librarian shall have the custody of the publications of the Academy. With the advice and consent of the President, he may effect exchanges with other associations.

See Chap. iv, art. 1; chap. xi.

CHAPTER IX

The Editor and the Publications

Article 1. The Editor shall have charge of the conduct through the press of the publications of the Academy. Together with the Committee on Publication he shall determine the contents of the publications.

Article 2. The publications of the Academy shall be as follows:

(i) The Proceedings shall be published at least semi-annually as soon as may be possible after the Annual May Meeting, and the stated December meeting next following, and shall contain a record of each stated or special meeting of the Academy. They shall be known respectively as the Summer and Winter number of the Proceedings.

The Summer number of the Proceedings shall include reports of the officers and standing committees for the preceding year; a list of the officers, councillors and members of standing committees elected at the preceding Annual Meeting; and such other matter as the Publication Committee may approve.

The Winter number of the Proceedings shall include a current list

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of officers, councillors, standing committees, Fellows and Foreign Honorary Members; the Statutes of the Academy; the Act of Incorporation of 1780 and its amendments; and such biographical notices or other matter as the Committee on Publication may approve.

In the discretion of the Committee on Publication, interim numbers of the Proceedings may be issued for the publication of accepted serial papers or other scholarly material.

(ii) Memoirs, monographs and volumes of collected papers may be published from time to time.

(iii) The Bulletin of the American Academy of Arts and Sciences shall be published eight times each year preceding the stated meetings, containing notices of such meetings, communications from the Council or Officers, and such other matter as may be of timely interest to the Fellows.

ARTICLE 3. A copy of the Summer and Winter numbers of the Proceedings shall be mailed to each Fellow, Fellow Emeritus, and Foreign Honorary Member.

A copy of the Bulletin shall be mailed to each Fellow and Fellow Emeritus.

A copy of any Interim number of the Proceedings shall be mailed only to those Fellows, Fellows Emeriti, and Foreign Honorary Members, who shall make written request to the Secretary for that number.

ARTICLE 4. Fellows who pay or have commuted the Annual Dues, Fellows Emeriti, and Foreign Honorary Members shall be entitled, upon written request to the Librarian, to receive gratis one copy of each number of Proceedings, Memoirs, monographs or series of collected papers, published by the Academy, which have been issued after their election, and are available.

ARTICLE 5. Not more than Two hundred extra copies of each paper printed in the Proceedings shall be placed at the disposal of the author without charge.

ARTICLE 6. The Editor shall have the authority to expend for printing and other expenses of publication such sums as may be appropriated by the Academy for such purposes; also such sums as may be made available to him by the Council from any source for particular publications under the sponsorship of the Academy.

See Chap. iv, art. 1; chap. xi, art. 1 (vi).

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CHAPTER X

The Council

Article 1. The Council shall exercise general supervision over all affairs of the Academy not explicitly reserved to the Academy as a whole.

It shall consider all nominations of Fellows and Foreign Honorary Members duly sent to it by the Committee on Membership, and act upon them in accordance with the provisions of Chapter III.

With the consent of the person concerned it shall have power to present to the Academy a proposal to transfer in respect to status, Class, or Section.

Article 2. Nine members shall constitute a quorum.

Article 3. It shall act upon all resignations and forfeitures of membership in the Academy.

It shall appoint all agents and subordinates not otherwise provided for by the Statutes, prescribe their duties, and fix their compensation. They shall hold their respective positions during the pleasure of the Council.

It shall fill any vacancy caused by death, resignation or incapacity of any officer.

Article 4. It may appoint for terms not exceeding one year, and prescribe the functions of such committees of its number or of the Fellows of the Academy, as it may deem expedient, to facilitate the administration of the affairs of the Academy or to promote its interests.

Article 5. At the stated March meeting of the Academy it shall recommend for action the appropriations which in the opinion of the Council should be made for the ensuing fiscal year and the Annual Dues therefor.

It may recommend special appropriations at any Stated Meeting of the Academy, or at a Special Meeting, in the call for which such business shall have been included.

See Chap. ii, art. 2, 10; chap. iii, art. 1, 2; chap. iv, art. 1, 2; chap. v, art. 2, 3; chap. vi, art. 2, 3; chap. vii, art. 1, 2, 7; chap. ix, art. 6; chap. xi, art. 1; chap. xii, art. 1, 4, 6.

CHAPTER XI

Standing Committees

Article 1. At the Annual Meeting of the Corporation the following Standing Committees shall be elected by ballot of the Fellows to serve from the time of their election until their successors shall have been elected.

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(i) *The House Committee* shall consist of three Fellows who shall have general charge of maintaining the House of the Academy in suitable condition for the uses thereof approved by the Council.

The Chairman of the House Committee or his designate shall approve in writing all expenditures for repairs, services, supplies or operation of the House, including salaries of House Employees.

The House Committee, in consultation with the Treasurer, shall determine the equitable proportion of expense to be assessed for the use of the facilities of the House, which are approved by the Council for other than Academy activities.

(ii) *The Committee on Membership* shall consist of the President, *ex-officio*, as Chairman, and eight Fellows, not members of the Council, one from each Class to be elected annually to serve for two years, except that in the initial election one additional Fellow shall be elected from each Class to serve for one year only. It shall have the duties designated to it in Chapter III.

(iii) *The Committee on Meetings* shall consist of the President as Chairman, and the Secretary, *ex-officio*, and four other Fellows. It shall arrange for meetings of the Academy.

(iv) *The Committee on Finance* shall consist of the Treasurer, *ex-officio*, as Chairman, and four other Fellows. It shall have general oversight of the investments of the Academy.

(v) *The Auditing Committee* shall consist of two Fellows who shall audit the accounts of the Treasurer with power to employ an expert and to approve his bill.

(vi) *The Committee on Publication* shall consist of the Editor as Chairman, *ex-officio*, and four other Fellows, one from each Class. It shall have the authority and the responsibility of determining the contents and of effecting the printing of the Publications of the Academy as set forth in Chapter IX.

(vii) *The Permanent Science Fund Committee* shall consist of seven Fellows. It shall review all applications for grants addressed to it and shall from time to time recommend to the Council appropriate disbursements from the income received by the Academy from the Trustee of the Permanent Science Fund, for carrying out the purposes set forth in the Agreement and Declaration of Trust which governs the use of this Fund.

(viii) *The Rumford Committee* shall consist of seven Fellows. It shall invite applications for pecuniary assistance in support of researches in the fields of heat and light, including X rays, and it alone shall authorize the purchase of books, publications and apparatus at

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the charge of the income from the Rumford Fund. It shall biennially recommend to the Council a candidate for the reception of the Premium to be awarded in accordance with the Rumford trust, and shall generally see to the proper execution of this trust.

(ix) *The C. M. Warren Committee* shall consist of seven Fellows. It shall invite applications for pecuniary assistance from any person wishing to engage in research in any branch of chemistry and shall recommend to the Council such applications as seem to be worthy of aid, and such other disbursements from income of the C. M. Warren Fund as it deems appropriate to the advancement of research in chemistry.

(x) *The Amory Prize Committee* shall consist of seven Fellows. It shall consider persons eligible and recommend to the Council the award by the President and Fellows of the Amory Prize and a gold medal or other token of honor and merit for each septennium beginning with that which was concluded on November 10, 1933, and thereafter, said award being in recognition of an invention or other contribution in the medical field specified in and according to the terms of the bequest of Francis Amory.

ARTICLE 2. Each Standing Committee shall confine its recommendations and its expenditures to such sum in each fiscal year as shall have been notified to its Chairman by the Secretary of the Academy as appropriations voted by the Academy, or by the Treasurer as income available for its purposes.

ARTICLE 3. Each Standing Committee shall report to the Academy at the Annual Meeting its acts of the previous year.

See Chap. iii; chap. iv, art. 1, 3; chap. vi, art. 4; chap. vii, art. 1, 2, 4; chap. ix, art. 1, 2.

CHAPTER XII

MEETINGS, COMMUNICATIONS, AND AMENDMENTS

ARTICLE 1. There shall be annually eight Stated Meetings of the Academy, namely, on the second Wednesday of October, November, December, January, February, March, April, and May. Only at these meetings, or at adjournments thereof regularly notified, or at Special Meetings called for the purpose, shall appropriations of money be made or amendments of the Statutes be effected.

The Stated Meeting in May shall be the Annual Meeting of the Corporation.

Special Meetings shall be called by the Secretary at the request of the President, of the Council, or of ten Fellows having the right to

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vote; and notifications thereof shall state the purpose for which the meeting is called.

The Council shall have authority, as occasion may demand, to arrange additional meetings and to cancel any of the Statutory meetings, except that meetings for transacting business shall be held as required by the Statutes.

ARTICLE 2. Except as otherwise provided, twenty-five Fellows having the right to vote shall constitute a quorum for the transaction of business at Stated or Special Meetings. Eighteen Fellows shall be sufficient to constitute a meeting for literary or scientific communications and discussions.

ARTICLE 3. Upon the request of the presiding officer or the Secretary, any motion or resolution offered at any meeting shall be submitted in writing.

ARTICLE 4. Fellows may introduce guests at any of the literary or scientific meetings of the Academy.

ARTICLE 5. All amendments to the Statutes, whether proposed by Fellows or by the Council, shall be considered by the Council and reported with recommendations for action to the Academy. At a subsequent Stated Meeting, or at a Special Meeting called for the purpose, the notice for which in either case shall state this proposed amendment, the Academy shall act upon the amendment. Two-thirds of the Fellows present, in a meeting of not less than forty Fellows, must vote in the affirmative to enact the amendment.

See Chap. ii, art. 6, 10; chap. iii, art. 1, 2; chap. iv, art. 1, 3, 4, 5; chap. v, art. 1; chap. vi, art. 2, 3; chap. vii, art. 2, 5; chap. ix, art. 2; chap. x, art. 5; chap. xi, art. 1, 3.

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CHARTER OF INCORPORATION

An Act to incorporate and establish a Society for the cultivation and promotion of Arts and Sciences. Granted May 4, 1780, by an Act of the Legislature of Massachusetts, and amended by the Acts of 1910, 1911, 1931, and 1947.

As the Arts and Sciences are the foundation and support of agriculture, manufactures, and commerce; as they are necessary to the wealth, peace, independence, and happiness of a people; as they essentially promote the honor and dignity of the government which patronizes them; and as they are most effectually cultivated and diffused through a State by the forming and incorporating of men of genius and learning into public societies for these beneficial purposes.

Be it therefore enacted by the Council and House of Representatives in General Court assembled and by the authority of the same, that [sixty-two persons][1] be, and they hereby are formed into, constituted, and made a body politic and corporate, by the name of THE AMERICAN ACADEMY OF ARTS AND SCIENCES, and that they, and their successors, and such other persons as shall be elected in the manner hereafter mentioned, shall be and continue a body politic and corporate, by the same name forever.

And be it further enacted by the authority aforesaid, that the Fellows of the said Academy may from time to time elect a President, one or more Vice-Presidents, one or more Secretaries, and such other officers of the said Academy as they shall judge necessary or convenient; and they shall have full power and authority from time to time to determine and establish the names, number, and duties of their several officers, and the tenure or estate they shall respectively have in their offices; and also to authorize and empower their President, or some other Fellow of the Academy, at their pleasure, to administer such oaths to such officers as they shall appoint and determine, for the well-ordering and good government of the said Academy, provided the same be not repugnant to the laws of this State.

And be it further enacted by the authority aforesaid, that the Fellows of the said Academy shall have one Common Seal, which they may make use of in whatsoever cause or business shall concern the Academy, or be relative to the end and design of its institution; and shall have power and authority from time to time to break, change, and renew the Common Seal, at their pleasure; and that they may sue and be

[1] For the names of the Fellows incorporated, see Memoirs, Vol. XI, Part I, pp. 33, 34.

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sued, in all actions, real, personal, and mixed, and prosecute and defend the same unto final judgment and execution, by the name of the President and Fellows of the American Academy of Arts and Sciences.

And be it further enacted by the authority aforesaid, that the Fellows of the said Academy may from time to time elect such persons to be Fellows thereof, as they shall judge proper, and that they shall have full power and authority from time to time to suspend, expel, or disfranchise any Fellow of the said Academy who shall by his conduct render himself unworthy of a place in that body, in the judgment of the Academy; and also to settle and establish the rules, forms, and conditions of election, suspension, expulsion, and disfranchisement.

And be it further enacted by the authority aforesaid, that the Fellows of the said Academy shall have full power and authority from time to time to make and enact such reasonable rules, orders, and bylaws, not repugnant to the laws of this State, as shall be necessary or convenient for the well-ordering and good government of the said Academy, and to annex reasonable pecuniary fines and penalties to the breach of them, not exceeding the sum of *twenty pounds,* to be sued for and recovered in any court of record within this State, in the name and for the use of the President and Fellows of the said Academy; and the same rules, orders, and bylaws to repeal at their pleasure; and also to settle and establish the times, places, and manner of convening the Fellows of the said Academy; and also to determine the number of Fellows which shall be present to constitute a meeting of the said Academy. *Provided,* that the Fellows of the said Academy shall meet twice in a year at the least; and that the place of their meeting shall never be more than thirty miles distant from the town of Boston.

And be it further enacted by the authority aforesaid, that the Fellows of the said Academy may, and shall forever hereafter, be deemed capable in the law, of having, holding, and taking in fee-simple, or any less estate, by gift, grant, devise or otherwise, any lands, tenements or other estate real and personal. *Provided,* that the said real estate shall not exceed in value the sum of *two hundred thousand dollars,* and the said personal estate shall not exceed in value the sum of *five hundred thousand dollars,* all the sums mentioned in the preceding section of this act to be valued in silver at the rate of *six shillings and eightpence* by the ounce. And the annual interest and income of the said real and personal estate, together with the fines and penalties aforesaid, shall be appropriated for premiums to encourage improvements and discoveries in agriculture, arts, and manufactures, or for other purposes consistent with the end and design of the institution of the said Academy as the Fellows thereof shall determine.

And be it further enacted by the authority aforesaid, that the end and

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design of the institution of the said Academy is, to promote and encourage the knowledge of the antiquities of America, and of the natural history of the country, and to determine the uses to which the various natural productions of the country may be applied; to promote and encourage medical discoveries; mathematical disquisitions; philosophical inquiries and experiments; astronomical, meteorological, and geographical observations; and improvements in agriculture, arts, manufactures, and commerce; and, in fine, to cultivate every art and science which may tend to advance the interest, honor, dignity, and happiness of a free, independent, and virtuous people.

And it is further enacted, that the place where the first meeting of the Fellows of the said Academy shall be held shall be the Philosophy Chamber in the University of Cambridge; and that the Honorable James Bowdoin, Esq. be, and he hereby is authorized and empowered to fix the time for holding the said meeting, and to notify the same to the Fellows of the Academy.

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VISCOSITIES TO 30,000 kg/cm²

By P. W. Bridgman

FURTHER ROUGH COMPRESSIONS TO 40,000 kg/cm², ESPECIALLY CERTAIN LIQUIDS

By P. W. Bridgman

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VISCOSITIES TO 30,000 kg/cm²

By P. W. Bridgman

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Introduction

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In a former paper[1] the viscosity of some 40 liquids was measured to 12,000 kg/cm². It was found that for most of these liquids viscosity increases to a first approximation exponentially with pressure—that is, the logarithm of the viscosity is a linear function of pressure. To a second approximation, for most of the liquids, the plot of logarithm of viscosity against pressure is at low pressures concave toward the pressure axis, but at higher pressures the curvature reverses, the curve becoming convex toward the pressure axis, and the viscosity increasing more rapidly than exponentially with pressure. The reversal of curvature usually occurs at a lower pressure for liquids with complicated molecular structure and with large absolute values of viscosity. For some of the simpler liquids formerly examined the reversal of curvature had not taken place below 12,000 kg/cm².

The techniques being now available for a considerable extension of pressure range,[2] the problem presents itself of extending former viscosity measurements to the widest possible range of pressure. There are at least two reasons for this. There is, in the first place, the purely practical matter of knowing what the viscosities at high pressures are of the liquids which have been used to transmit pressure. For example, in measuring compressibilities with the sliding wire method, effects were encountered a number of times which strongly suggested that the transmitting liquid was becoming so viscous under presssure as to interfere with the proper functioning of the apparatus immersed in it. How important this effect is can be answered by actual measurements of the viscosity of the transmitting liquid under pressure. In the second place, there is theoretical interest in finding whether the more rapid than exponential increase of viscosity found in the lower pressure range continues over the wider range.

The number of liquids available for measurement over the full range up to 30,000 kg/cm² is much restricted because of freezing induced by

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pressure. In the following, five pure liquids have been measured over the full range: methyl, n- and i-propyl, n-amyl alcohols, and i-butyl bromide. These are nearly the only ones of the forty-three liquids of the former investigation available over the new range. The propyl and amyl alcohols are beyond their freezing points under these conditions, but support the necessary subcooling without the formation of nuclei of the solid. The first two even alcohols, on the other hand, ethyl and butyl alcohols, would not support supercooling without freezing under the conditions of these measurements, and could not be used. Beside these five, the pressure transmitting liquid was also studied; this has been a mixture in various proportions of Eastman's "technical" i-pentane with "pentane." In the light of these measurements it has become possible to improve somewhat the functioning of the transmitting liquid.

In addition to the measurements over the full pressure range on the liquids just enumerated, opportunity was taken to study the effect of pressure on a class of liquids not available at the time of the former measurements, namely various dimethyl siloxane polymers made by the Dow Corning Company, and also some of their commercial "Dow-Corning fluids." Apart from the theoretical interest in these liquids, there is the practical question of whether they would not be suitable for pressure transmitting liquids. They have already been used in this capacity at higher temperatures, above 200° C., for which they are especially adapted, but hitherto not at pressures above 5,000 kg/cm^2. The result of the present study is that the viscosity of these liquids, even the lowest members of the series, increases with abnormal rapidity with pressure, so that they are not suitable to replace pentane as a pressure transmitting medium in the ordinary range of temperature.

Apparatus and Method

The general scheme of the method is the same as before, namely a mechanical member falling under gravity through the liquid, the time of fall being determined by the breaking and making of an electrical contact. The fact that now the high pressure container has to be in a single piece, however, demands essential geometrical modifications in the arrangements. As before, the pressure apparatus is mounted on an axis, so that it can be rotated back and forth through 180°. The axis of rotation is the longitudinal axis of hydraulic presses and high pressure vessel. During rotation the hand pumps by which pressure is generated are disconnected, pressure being maintained by closing appropriate valves. The falling member, instead of being a cylindrical weight falling vertically in a concentric cylinder, is now a vane or a bar, pivoted about an offset longitudinal axis, as indicated in Fig. 1.

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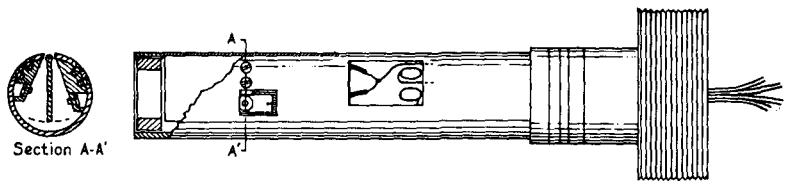

FIGURE 1. The swinging vane apparatus for measuring viscosity.

The vane rotated between stops, which were insulated and served at the same time to provide the electrical contact. The angle of rotation between stops was about 60°. The width of the vane was 1.0 cm. and its length 2.5 cm. By varying the thickness of the vane the fall time may be varied and adapted to the viscosity of the liquid. In this work two vanes were used—one of steel 0.003 inch thick, and the other of steel 0.030 inch thick. The time of fall of the latter was about eight times that of the former. This ratio was not enough to cover the whole range of viscosities. For the highest pressures and the most viscous liquids the heavy vane was replaced by a bar of gold, 3 mm. in diameter and 2.5 cm. long, attached to the axis by two light arms, approximately 8 mm. long. The fall of the gold bar was about forty-five times more rapid than that of the 0.030 vane. The observed fall times varied from a minimum of about 2 seconds, below which the natural frequency of the timing apparatus introduced too large errors, to a maximum of about 6,000 seconds. The total range of viscosity observed in the pressure apparatus was therefore 8 x 45 x 3000, or approximately one million fold.

Making and breaking of contact was indicated by the swing of the needle of a conventional portable voltmeter of about one second period connected in series with a B battery of 22.5 or 45 volts. Timing was with a stop watch by observing the swing of the needle of the voltmeter. The axis of the vane was positively grounded through a 0.001 copper wire, so that the contacts were definite and all metallic. This constituted a distinct advantage over the contact arrangements of the falling weight of the former experiments in which part of the circuit might be through the thin layer of liquid at the lug of the falling weight.

For most of the liquids even the thinnest vane, 0.003 inches, gave too short fall times at atmospheric pressure. Connection was made with the atmospheric viscosity by an auxiliary apparatus. This consisted of a length of precision bore pyrex tubing from the Fish-Schurman Corporation. The internal diameter was about 0.25 inch, and the length about 15 inches. This was mounted vertically in a temperature bath, and filled with the liquid in question. Relative vis-

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cosities were obtained by timing the fall in the tube of a cylindrical aluminum weight with hemispherical ends. The weight was kept concentric, so that the fall was without yawing, by three small lugs at top and bottom. Observation of the fall time was made at 20° and 25° so as to provide the data for temperature correction to the pressure runs, which were made at room temperature, usually between 23° and 24°. Relative viscosities were converted to absolute viscosities by observing the time of fall in distilled water. Connection was made between the times in the atmospheric apparatus and the pressure apparatus by observing the time in both pieces of apparatus with a liquid viscous enough to give a long enough time for accuracy in the vane apparatus. This liquid was a heavy lubricating oil. The vane apparatus and the falling weight apparatus at atmospheric pressure differed by a further factor of about 500 in the equivalent fall times, so that altogether viscosities were measured over an extreme range of 5×10^8. This is much greater than the extreme range of observed viscosities of the former work, which was about 1,000 fold. It is true that in the former paper a pressure effect of 10^7 was mentioned (for eugenol), but this was by an extrapolation.

The entire pressure apparatus was filled with the liquid to be measured. It would have been too complicated in the small dimensions available to attempt to separate the transmitting liquid from the liquid to be measured, as was done formerly. The manganin gauge for measuring pressure was therefore also immersed in the same liquid, and this further demanded that the liquid be a sufficiently good electrical insulator. This procedure would not have been possible formerly with some of the alcohols, which were conductive enough to disturb the readings of the manganin coil. However, this effect fortunately did not prove troublesome at the higher pressures used here—the "water kick" in the reading of the coil almost entirely disappearing at pressures above 10,000 kg/cm^2.

Different set-ups with different vanes had to be made for different pressure ranges with the same liquid. Thus with i-propyl alcohol the range from 5,000 to 15,000 kg/cm^2. was covered with the 0.003 inch vane, the range from 15,000 to 25,000 with the 0.030 inch vane, and the range from 18,000 to 29,000 with the gold bar. The logarithms of the fall times were plotted against pressure, with the addition of an appropriate constant for each range so that the observed points overlapped smoothly from one range to the next. When the additive constant was determined in this way, it also resulted that all the points for the three ranges lay on a single smooth curve, thus affording evidence of the consistency of the measurements. The logarithmic constant in the lowest range was so determined as to piece on smoothly

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with the former measurements in the range up to 12,000. This again was always possible. In the illustrative example of i-propyl alcohol, shown in Figure 2, there are checking measurements in the range between 5,000 and 12,000 for the two sets of measurements, by different methods and separated by 23 years in time. The slightly divergent point near 5000 was because the fall time (with the vane) was too short. The check was in all cases most gratifying; the order of the agreement is indicated in Figures 2 and 3.

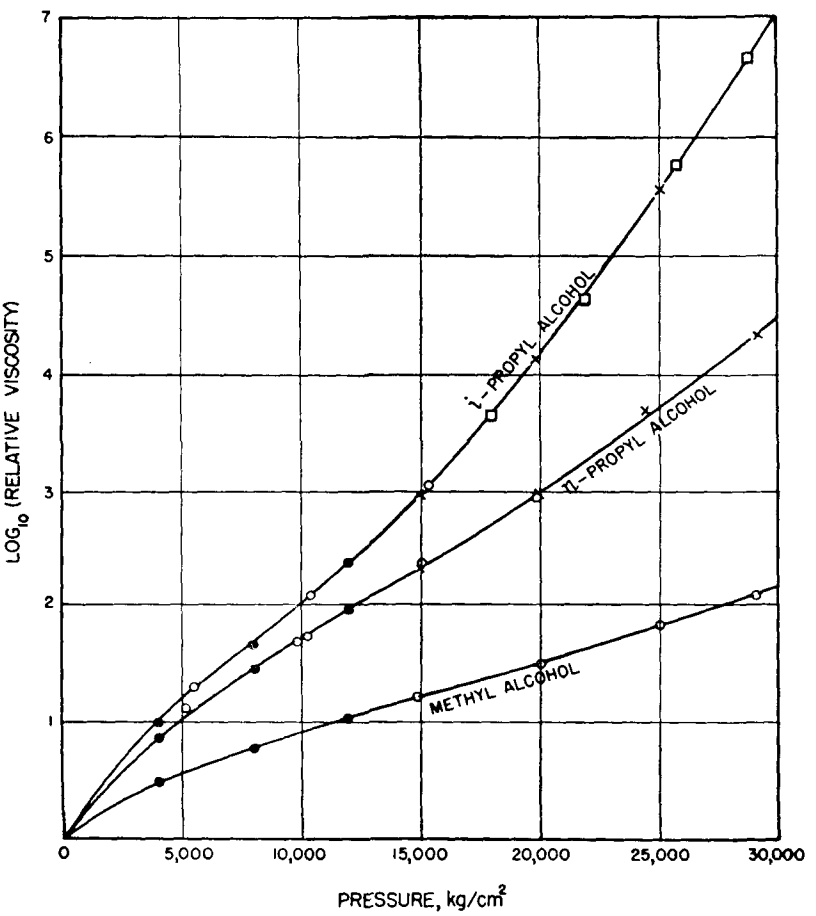

FIGURE 2. Logarithm of relative viscosity of methyl, n-propyl and i-propyl alcohols as a function of pressure (room temperature). See text for the symbols.

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The observed fall times are proportional to the viscosity except for two correction terms—one depending on the buoyancy of the liquid, and the other on the change of linear dimensions of the apparatus produced by hydrostatic pressure. A simple dimensional analysis shows that viscosity is proportional to time multiplied by the linear dimensions of the apparatus multiplied by the difference of density of the vane and the liquid. Since the compressibility of both steel and the liquids is known, the correction factors may be determined. At 30,000 the additive correction on the logarithm of the fall time varies from a minimum of -0.018 for the lighter liquids, to -0.040 for ethyl bromide. On a total logarithm varying from 5 to 6 this correction is almost negligible.

Of the liquids measured in the following, all except the siloxanes were regular Eastman chemicals, used without attempt at further purification. The n-amyl alcohol was designated as "practical." The dimethyl siloxane polymers and the Dow Corning fluids I owe to the courtesy of Mr. Shailer L. Bass of the Dow Corning Corporation. The pure individuals were specially prepared by fractional distillation, of which those embracing 2 to 8 silicons in the chain were furnished. Of these the trimer, $Si_3O_2(CH_3)_8$, tetramer, $Si_4O_3(CH_3)_{10}$ hexamer, $Si_6O_5(CH_3)_{14}$, and octamer, $Si_8O_7(CH_3)_{18}$, were measured for viscosity. The compressibility of all of them has also been measured.[3] The first of the series, the dimer, was not measured for viscosity because it freezes at a low pressure. It was a surprise that none of the higher members of the series were brought to freeze at any pressure, either by pressures up to 12,000 in the present viscosity measurements, or by pressures up to 40,000 in the compressibility measurements. The reason for this should be investigated further.

The Experimental Results

In Figures 2, 3, 4, and 5 the experimental results are shown graphically, with the individual points. In these figures the logarithm to the base ten of the relative viscosity, corrected as described, is plotted against pressure in kg/cm^2. The points obtained with different set-ups are differently designated; those with the 0.003 inch vane by an open circle, those with the 0.030 inch vane by a cross, and those with the gold bar by a square. Solid circles show points on the curves obtained in the previous measurements up to 12,000. Smooth curves were drawn through the experimental points, and the numerical values at regular pressure intervals read off and tabulated in Tables I to III.

In Figure 2, the results are shown for methyl, n-, and i-propyl alcohols, and in Figure 3 for n-amyl alcohol, n-butyl bromide, and

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i-pentane. The numerical results are collected in Table I. In all cases logarithm of viscosity against pressure turns upward at high pressures, although the upturn may be deferred to as much as 20,000 kg/cm² for methyl alcohol. The largest effect at 30,000 is shown by i-propyl alcohol, for which the viscosity has increased nearly 10^7 fold (extrapolated from 29,000). Initially, however, the rate of rise for i-propyl alcohol is not as rapid as for n-amyl alcohol, the two curves crossing in the neighborhood of 20,000.

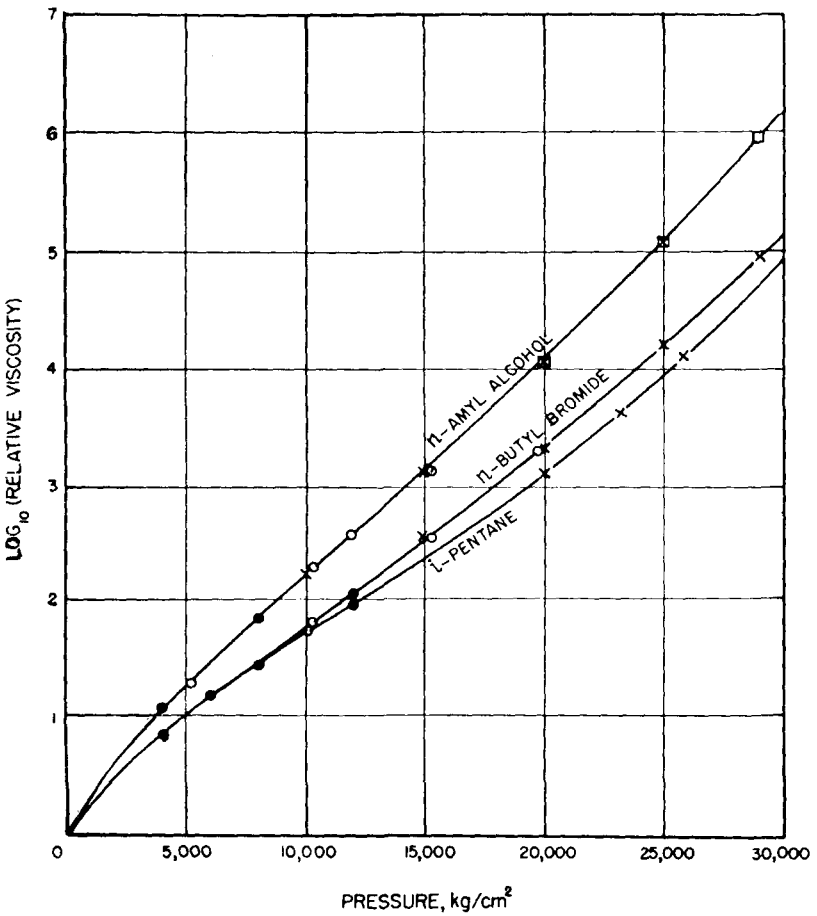

FIGURE 3. Logarithm of relative viscosity of n-amyl alcohol, i-pentane, and n-butyl bromide as a function of pressure. See text for the symbols.

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TABLE I

Pressure kg/cm²	Log_{10} (Relative Viscosity)					
	Methyl Alcohol	n-propyl Alcohol	i-propyl Alcohol	n-amyl Alcohol	n-butyl Bromide	i-pentane
0	0.000	0.000	0.000	0.000	0.000	0.000
5,000	0.650	1.014	1.168	1.290	1.004	1.026
10,000	0.890	1.684	1.990	2.224	1.722	1.720
15,000	1.200	2.328	2.960	3.150	2.548	2.342
20,000	1.482	2.966	4.116	4.096	3.326	3.122
25,000	1.810	3.708	5.490	5.100	4.228	3.980
30,000	2.152	4.500	6.986	6.192	5.146	4.930

TABLE II

VISCOSITY OF SEVERAL DIMETHYLSILOXANE POLYMERS

Pressure kg/cm²	Log_{10} (Relative Viscosity)			
	Trimer	Tetramer	Hexamer	Octamer
0	0.00	0.00	0.00	0.00
2,000	0.86	0.94	0.98	1.01
4,000	1.50	1.63	1.73	1.83
6,000	2.13	2.40	2.66	2.87
8,000	2.94	3.53	4.05	4.52*
10,000	4.19	5.26	6.46	6.03
12,000	6.39	——	——	——

* at 9,000

TABLE III

VISCOSITY OF SEVERAL "DOW-CORNING FLUIDS"

Pressure kg/cm²	Log_{10} (Relative Viscosity)			
	500–1.00	500–2.00	500–12.8	200–100
0	0.00	0.00	0.00	0.00
2,000	0.86	0.98	1.13	1.05
4,000	1.50	1.73	2.15	2.15
6,000	2.13	2.63	3.57(a)	2.87(b)
8,000	2.95	3.91	4.66	——
10,000	4.26	——	——	——

(a) at 7,000 (b) at 5,000

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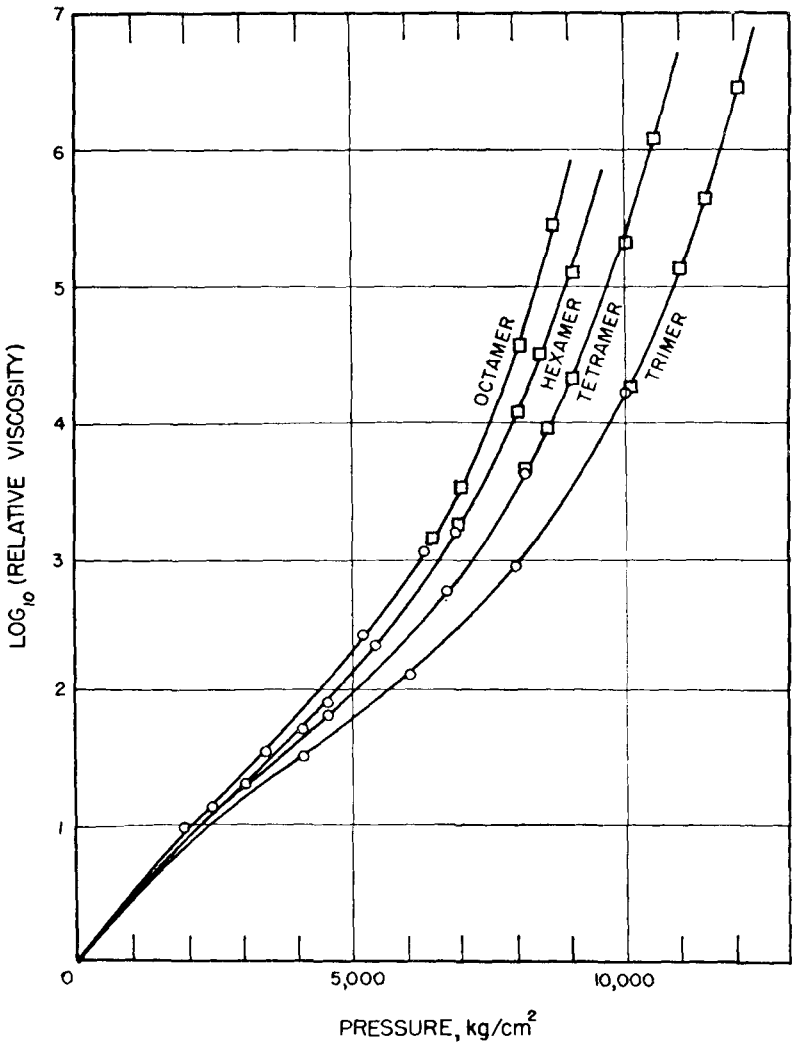

FIGURE 4. Logarithm of relative viscosity of four dimethyl siloxane polymers. See text for the symbols.

The results obtained with the mixtures of pentanes are not reproduced in detail here, since the material was not well enough defined to have scientific significance, nor were the measurements as complete over the full range. From the point of view of technique, however,

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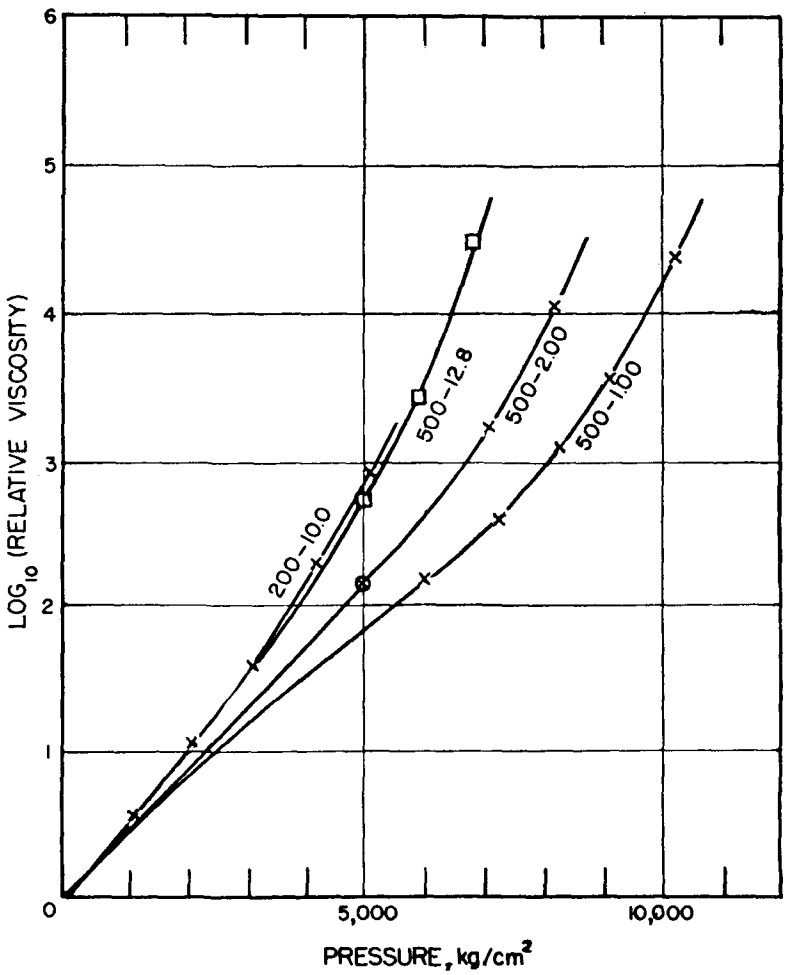

FIGURE 5. Logarithm of relative viscosity of several "Dow-Corning fluids." See text for symbols.

it is worth mentioning that a mixture of equal parts of Eastman's i-pentane and "pentane" ("technical") is at 30,000 less viscous than Eastman's i-pentane by a factor of 2, and pure "pentane" is less viscous than i-pentane by a factor of 3.5. Furthermore, the "pentane" did not freeze under these conditions at room temperature, so that it may well replace i-pentane or mixtures as the pressure transmitting

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liquid. The absolute viscosity of i-pentane at 30,000 at room temperature is about 170 poises.

In Figure 4 and Table II the results are shown for four pure dimethyl siloxane polymers, the trimer through the octamer, and in Figure 5 and Table III for several "Dow Corning Fluids" of the 500 and 200 series, which are mixtures of the dimethyl siloxane polymers. The corrections for buoyancy and change of linear dimensions were so small for these liquids that they were not applied. The effect of pressure is so large on this class of substance that no attempt was made to carry the pressures above 12,000. Not only is the effect of pressure large, but the curvature is in all cases much greater than for any of the liquids of Table I, and the upturn begins at much lower pressures. This is all in accordance with results previously found, namely that the pressure effect and the curvature is greater for substances with more complicated molecules. This general trend is particularly well brought out in Figure 4 for the pure species. Another feature evident from the figures is that all members of the series have very approximately a common initial tangent at atmospheric pressure.

The very large pressure effect makes these liquids unsuitable for pressure transmitting media at high pressures, in spite of other desirable characteristics. Thus at atmospheric pressure the lowest member of the series which does not freeze under pressure, the trimer, is five times more viscous than i-pentane, whereas at 10,000 kg/cm² it has become 5,000 times more viscous.

Summary and Discussion

In this paper measurements of viscosity have been extended over a 2.5 fold increase of pressure range, from 12,000 to 30,000 kg/cm². The trends formerly found continue in the new range. Ultimately the viscosity increases with pressure more rapidly than exponentially. The pressure at which the upturn occurs is lower for liquids with more complicated molecules and the rate of upturn is more rapid.

The order of magnitude of the effect of pressure on viscosity is greater than that of any other known pressure effect, and would seem to indicate some essential difference in the mechanism. In viscous flow the molecules preserve their inviolability and must to a large extent function as individual wholes. In the case of long polymeric molecules, packed together like earth worms in a tin can, the phenomena of viscous flow must be quite different from those of specific heat or thermal expansion, for example, in which the parts of the molecules can function with a certain degree of independence. I have previously expressed this by saying that the pressure effect on viscosity involves an "interlocking" of the molecules. The accentuation of the effects

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now found on increasing the pressure range seem to me to only accentuate the necessity for some such mechanism. It would seem to me that some essential physical modification is necessary in the pictures back of analyses such as those of Frisch, Eyring, and Kincaid,[4] for example, in which viscous motion is supposed to involve the passage of an activated complex from one equilibrium position over an intermediate potential hill to a new equilibrium position. Formally, it would probably be possible to include the new sort of thing by assuming, as they themselves indicate, that the activated complex itself is an aggregate of molecules, the degree of aggregation itself increasing rapidly with pressure. But physically it would seem that this is pretty close to the "interlocking" effect.

I am indebted to my mechanic, Mr. Charles Chase, for skillful construction and setting up of the apparatus.

LYMAN LABORATORY OF PHYSICS,
Harvard University, Cambridge, Mass.

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FURTHER ROUGH COMPRESSIONS TO 40,000 kg/cm², ESPECIALLY CERTAIN LIQUIDS

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INTRODUCTION AND TECHNIQUE

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In this paper former rough measurements[1] of compression to 40,000 kg/cm² at room temperature of a number of solids are extended to substances initially liquid, the measurements in many cases being carried through the freezing point and on into the solid phase. This extension to the liquid phase has been made possible by a small change in technique, by which the liquid is sealed inside a lead capsule, and the overall compression of capsule with its contained liquid determined. A similar technique was formerly used in measurements to 50,000 over a temperature range,[2] but with a modification of detail. Formerly the lead capsule was sealed with a condenser discharge at the moment of impact of a lead plug pressed against the body of the capsule. With the present arrangement the walls of the capsule are so thin, the total thickness of the capsule being only 0.130 inch, as shown in Fig. 1, that the impact of the sealing plug would produce undue distortion and consequent mechanical extrusion of the liquid. Some less violent method of making the seal is therefore required. Ordinary soft soldering is ruled out for the same reason as before, namely too rapid heat transfer, with resulting thermal expansion and escape of the liquid.

The new technique employs essentially a cold soldering. The lead sealing point is lightly amalgamated with mercury, then lightly pressed against its seat in the capsule at the same time that it is rotated so as to spread the amalgamation to the seat, and finally held pressed against the seat with light pressure for 18 hours or more. By this time the mercury has diffused into the lead, leaving a solid solution, which is strong enough to withstand without leak the distortion of the capsule incident to carrying it to 40,000 and back, one or even several times. Lead is unique among all the soft metals whose binary mixture diagrams are given in Hansen[3] in the width of the range of composition in which the homogeneous solid solution is stable. Most soft metals

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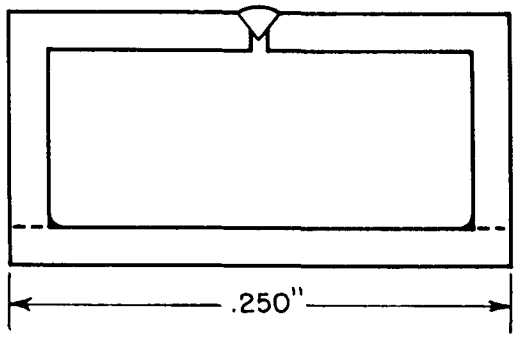

FIGURE 1. Scale drawing of the lead capsule for containing the liquid for measurements of compression. The seal is made by cold amalgamation under slight pressure of the conical plug.

break up into a liquid phase when amalgamated with mercury, so that the seal is not made. The cold amalgamation seal with lead was successful at once for nearly all the liquids tried. For some it was more difficult than for others, apparently the liquid itself forming some sort of surface film on the lead which was difficult to break through so as to obtain a contact sufficiently close for the solid sulution to grow across the surface. Several liquids were tried three or four times before success was attained, and there were one or two which were finally abandoned. Success was apparently easier to achieve if a slight amount of sodium was dissolved in the mercury, a practise long familiar in amalgamating copper for electrical contacts.

The methods of computation were simple extensions of those used before. The measured displacement of the piston has to be corrected for distortion of the carboloy piston and the compression of the lead sheath and of the steel washers. The total corrections were of the general order of 25% of the measured displacement. The initial volume of the liquid was calculated from its weight and density, the latter obtained either from the International Critical Tables or by special measurement in a specific gravity bottle.

It is characteristic of the compression of liquids that the initial increment of pressure is accompanied by a comparatively large volume change, the compressibility rapidly dropping at higher pressures. This means that the error from the friction exerted by the lead capsule is especially large at the low pressure end of the range. Furthermore, it is especially important to know the initial volume accurately, since this sets the fiducial mark from which all subsequent proportional changes of volume are calculated. The result was that it was neces-

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sary to supplement the measurements in the 40,000 apparatus with other measurements in an apparatus especially constructed for the initial range from atmospheric pressure up to 5,000 kg/cm². The primary function of this supplementary apparatus for 5,000 was the same as that of the 40,000 apparatus, namely to permit rapid measurements with moderate accuracy, so that it can be used as a tool for exploration.

The supplementary apparatus is shown in Figure 2. The liquid whose compression is to be measured is placed in the heavy steel cylinder A. Pressure is produced by advance of the piston, P, ½ inch in diameter, and the volume change is given directly by the motion of the piston measured by a dial gauge graduated to 0.001 inch and reading by estimation to 0.0001 inch. This gauge is so connected to the cylinder and the mushroom plug as to minimize any distortion in the steel parts and so as not to include at all any compression in the rubber packing on the end of the piston, which operates on the unsupported area principle. The compressing piston P is driven by a second piston B, 2.0 inches in diameter, thus affording a sixteen fold multiplication in pressure. The piston B is driven by a conventional hand pump, connected through a dead weight piston gauge. The pressure is controlled by the weight on the piston of the dead weight gauge, the weight being adjusted and then the pump operated until the weight floats. Readings were made at eleven different pressures between atmospheric and 5,000, the spacing being nonuniform and closer at the lower end of the range. Readings were made with increasing and decreasing pressure, 20 in all, in order to eliminate error from friction. A special feature of this apparatus, not used in any other of my pressure apparatus, is the provision for rotating the pistons P and B before each reading to minimize the effect of friction. To this end the packing on the mushroom heads of both P and B is made unusually thin, only 1/64 inch thick on each. The packing material was usually neoprene, but for some liquids which attack neoprene, such as xylene, varnished cambric, such as is used in electrical insulation, was successfully used, in three thicknesses, each .007 inch thick. The washers must obviously be cut with care, using a sharp cutter to obtain a smooth edge. Use of such thin packing demands that the inner surfaces of the cylinders in which P and B play be well polished.

Rotation was by hand, with a lever passing through a hole in the piston B, back and forth through an angle of 60°. Usually three double oscillations were made before each reading. It is not possible with this apparatus, in contrast to the 40,000 apparatus, to make readings as fast as the pressure manipulations can be made, but after every increase of pressure an appreciable time must elapse for dissipation of

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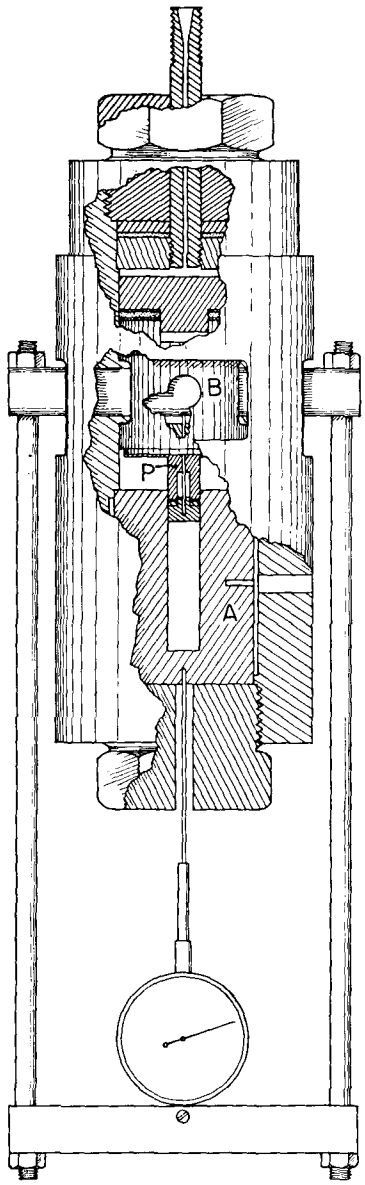

FIGURE 2. The apparatus for rapid determination of the compression of liquids up to 5,000 kg/cm². Friction is minimized by rotation of the pistons P and B before the readings.

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the heat of compression. The time may be decreased by placing in the body of the liquid several strips of sheet copper to conduct away the heat. In this way the time between readings was reduced to two minutes. The readings were taken on an exact time schedule to make the conditions as reproducible as possible. By taking all precautions, the difference between readings with increasing and decreasing pressure was practically never as much as 0.001 inch, and often materially less, on a total stroke of 0.5 inch. Friction should be reduced from the mean of readings as close together as this to a value smaller than that of the other errors.

The piston readings were converted to absolute compressions by means of blank runs with solids and liquids of known compressions in a way which need not be described in detail. The time required for a complete run was of the order of one hour, somewhat less than that required with the 40,000 apparatus. Operation so far has been confined to room temperature, which in the following may be taken as 25°, but there is no reason why temperature control and operation at other temperatures should not be added; in fact, a modified apparatus is now under construction for use at other temperatures. The time for a run will now naturally be increased by the time required for attainment of temperature equilibrium at each temperature.

The apparatus may be used for determinations of the thermodynamic freezing parameters of those liquids which freeze within the range by placing the liquid in an inverted steel cup with mercury seal, with water to transmit the pressure to the mercury, after the fashion of my early freezing curve determinations.[4] The apparatus was so used for a number of substances to be described in the following. By carrying the measurements beyond the freezing pressure up to 5,000, compressions of the solid phase are also obtained. The accuracy of these determinations is somewhat reduced as compared with that of the compressions of non-freezing liquids because of the reduced amount of liquid allowed by the presence of the water, mercury, and steel. In certain cases the freezing parameters had been previously determined in other apparatus better adapted to giving accurate values. In these cases the present data were adjusted to agree with the former results in the overlapping range, as will be described in detail later. There are also some cases in which compressions have been previously measured in the range from 5,000 to 50,000 kg/cm², but in which the low pressure range was not measured. The new data supplemented with the old now can allow complete values of compressions from atmospheric pressure to 40,000 kg/cm². The freezing temperatures and pressures given in the various tables have only an inferior accuracy, since the pressure steps were not made small enough to give good

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values, the smallest being 200 kg/cm^2. The differences of volume between liquid and solid are the differences at the temperature (25°) and the pressure indicated, and should be fairly good for these conditions. They are *not* the volume differences for the correct equilibrium pressure at 25°, but differ from this by a term equal to the product of the pressure excess (or defect) and the difference of compressibility between liquid and solid.

The Materials

The materials measured in the following include in the first place 30 hydrocarbons. It was thought to be of interest to find whether the compressions, particularly at the high pressure end of the range, tend to assume any simple relation to the obvious properties of the molecule. The 30 hydrocarbons selected include all those listed in Eastman's catalogue of organic chemicals and procurable, including substances both liquid and solid under ordinary conditions. Most of these were of the "Eastman" grade of purity; the n-dodecane, n-hexadecane, and tetrahydronaphthalene were of "practical" grade, the amylene and fluorene of "technical" grade, and the styrene was "stabilized with tert.-butylcatechol." Next comes a group of 8 miscellaneous organic compounds. The first six of these were from my own stock, left from previous experiments, which seemed of interest for various reasons. In addition there are two of the fluorocarbons developed during the war, which I owe to the courtesy of Professor W. T. Miller of Cornell University. The first of these is perfluoroheptane, C_7F_{16}, prepared by the vapor phase fluorination of heptane, utilizing the procedure of Cady, Grosse, Barber, Binger, and Sheldon.[5] It boiled at 82°. The second is a "chlorofluorocarbon polymer oil." This was a fraction of "stabilized" chlorotrifluoroethylene polymer of approximate boiling range 100° to 200° at 0.3 mm, prepared as described by Miller, Dittman, Ehrenfeld, and Prober.[6] Finally there is a group of 16 substances which I owe to the courtesy of Mr. Shailer L. Bass of the Dow Corning Co.. The first seven of these are the individual members of the dimethylsiloxane polymers from the dimer through the octamer, or in other words the compounds of the formula

$$(CH_3)_3SiO-\left[(CH_3)_2SiO\right]_x-Si(CH_3)_3$$

where x varies from 0 through 6. The next eight are commercial "Dow Corning" fluids of the 500 and 200 series of different viscosities. The members of these two series are composed predominantly of polymers of the type just described. In the following these liquids are identified in the regular manner by giving first the number of the series and then the viscosity in centistokes. Thus the liquid

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designated as 500–2.00 is the liquid belonging to the 500 series with viscosity 2.00 centistokes. Finally, there is a single member of the 550 series, which is a different type of compound than the others, in that a portion of the methyl groups are replaced by phenyl groups.

Comparison with Previous Measurements

The volume compression of liquid n-heptane has been previously measured[7] by the sylphon method at 0°, 50°, and 95° in the range of the liquid below 11,000 kg/cm². Exact comparison with the present measurements is not easy because of the incompatibility of temperature range. Linear interpolation of the previous results gives volume decrements at 500 and 5,000 kg/cm² of 0.0544 and 0.202 respectively against 0.0502 and 0.198 found now. The difference is in the direction to be expected because of the inadequacy of a linear interpolation, and does not appear unreasonable in magnitude.

The volume compression of liquid n-octane was previously measured[8] in the same way as n-heptane in the same temperature range, but of necessity in a narrower pressure range because of the freezing. Linear interpolation as above gives for the volume decrements at 500 and 3,000 kg/cm² 0.0444 and 0.149 respectively against 0.0444 and 0.146 found now. The agreement at 500 is too good for the method of interpolation, and at 3,000 not unreasonable.

The volume compression of liquid n-decane[9] was determined under the same conditions as outlined in the two paragraphs above, the pressure range being correspondingly reduced. The volume decrements at 500 and 1,000 kg/cm² by linear interpolation were 0.0417 and 0.0713 respectively against 0.0400 and 0.0683 found now. The difference is in the right direction, but somewhat larger than appears a natural consequence of the method of interpolation.

Three previous sets of measurements have been made on benzene in the course of my high pressure work, not to mention work by other observers.[10] The freezing parameters were determined with much care up to 12,000 kg/cm². These values are doubtless better than those obtained with the present apparatus, and they were accordingly accepted and incorporated in Table II. The fractional change of volume on freezing with the present apparatus was about 5 per cent lower than the value accepted from the previous work. The volume compression of the liquid was measured in the former sylphon apparatus, but only at 50° and 95°. The decrement at 24° and 680 kg/cm² (the freezing pressure at this temperature) was obtained by linear extrapolation from these two temperatures and is therefore rather uncertain. Finally, the volume decrement of the solid phase from 5,000 as the zero has been determined. The volume decrement

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between 5,000 and 40,000 formerly found was 0.141, against 0.144 found now and given in Table II. Exact comparison of these two results is not possible because the present results pertain to the low pressure modification of the solid, since no trace of the transition to a high pressure form was found which formerly occurred at 12,500 kg/cm^2. In the present work the transition was doubtless suppressed because of the small size of the apparatus and the low temperature, which was at the lower edge of the range in which the transition was previously observed. The volume decrement at the transition formerly found was 0.008. In comparing the previous results with the present for the low pressure modification the volume decrement is therefore to be taken as probably 0.149 at the maximum (assuming the two modifications to have the same compressibility), or somewhat less than 0.149 if the high pressure modification is assumed to be less compressible, as is probable. In any event the agreement with the former high pressure values is not bad.

The freezing pressure of cyclohexane at 25° listed in Table II, 355 kg/cm^2, is taken from Deffet[11]. There is no doubt that his value is better than the mean value 420 kg/cm^2, given by the present work. It has already been explained that the pressure steps in the present work were so large that a minimum error of 100 kg/cm^2 in the equilibrium pressure is always possible. The values above 5,000 given in the table are taken from my previous measurements[12] to 50,000. Measurements above 5,000 were not made with the present apparatus because cyclohexane was one of the liquids for which the sealing technique made so much difficulty that it was abandoned. With regard to the previous work it is to be especially noted that the volume discontinuity at 7,500 listed there was incorrectly described as due to freezing; it is, as a matter of fact, due to a transition between two solid phases.

The freezing pressure of p-xylene is so low that the values of other observers were used for the low pressure end of the range. The freezing pressure at 25° was taken as 343 kg/cm^2 from the work of Deffet,[13] and the fractional change of volume on freezing as 0.164 at the same pressure and temperature from the same author. The compression of the liquid at 343 kg/cm^2 was assumed to be 0.0249 from the work of Richards and collaborators,[14] this being their value at 20°. There should be a small correction for the difference of temperature, but the data for this do not exist. In connecting these low pressure values with the present measurements to 40,000 an extrapolation of the measurements on the solid of 1,000 kg/cm^2 was necessary. Measurements have been previously made on the solid phase of this sub-

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stance in the range above 5,000 kg/cm². The volume decrement between 5,000 and 40,000 formerly found was 0.113 against 0.116 found now.

Methylene chloride (Table III) has been previously measured[15] above 5,000, so that the essentially new contribution of the present measurements is the compression of the liquid up to 5,000. The former total volume decrement between 5,000 and 40,000 was 0.219 against 0.211 found now. The agreement above 15,000 is perfect within the number of significant figures. The former freezing parameters agree fairly well with the present ones.

The freezing parameters of chloroform have been previously measured[16] with considerable care; these former values are incorporated in Table III. The compression has also been determined from 5,000 as zero up to 50,000. The former value of the volume decrement between 5,000 and 40,000 was 0.204 against 0.203 found now.

Ethyl acetate has been previously measured[17] above 5,000. In the former measurements data were obtained for both liquid and solid phases up to the maximum pressure; the natural tendency is for the liquid to subcool over the entire pressure range, so that special manipulation was necessary to obtain the solid phase. With the present smaller apparatus and more rapid pressure variation the solid phase was not obtained at all. The former volume decrement of the liquid phase between 5,000 and 40,000 was 0.185 against 0.178 found now.

The compression of the liquid phase of chlorobenzene has been previously measured[18] at 0°, 50° and 95° up to 11,000 kg/cm². Reducing to 25° by linear extrapolation gives for the volume decrement at 5,000 and 25°, 0.1406 against 0.1517 found now. The discrepancy is perhaps in the direction to be explained by the linear extrapolation, but is larger than usual and not obviously explainable. Further, the volume decrements have been determined up to 50,000 from 5,000 as zero. The former volume decrement between 5,000 and 40,000 was 0.177 against 0.175 now. The correct freezing pressure at 25° is probably nearer 5,000 than 7,500, the average figure given by this work. It is to be marked that in the former work a second phase of the solid was encountered at pressures above 13,000 and at temperatures of 75° or more; no trace of this phase was found in the present work.

The compression of n-amyl ether has been measured[19] up to 50,000 from 5,000 as zero. The total volume decrement between 5,000 and 40,000 was 0.197 against 0.187 found now. The former freezing pressure given for 25° was 7,500, very materially lower than that now given, 11,140; neither of these values makes any pretense to accuracy. The former volume decrement at the freezing pressure, 0.047, is much higher than that now given, 0.021, but is not inconsistent with it in

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view of the difference of pressures, and indicates a compressibility for the liquid phase materially higher than that of the solid, as is normal.

The Results and Discussion

The results for the normal straight chain paraffins, containing 7, 8, 10, 12, 16, 18 and 28 carbons in the chain, are shown in Table I. The

TABLE I

Compressions of Normal Straight Chain Hydrocarbons

Pressure kg/cm²	$\Delta V/V_0$						
	n-heptane	n-octane	n-decane	n-dodecane	n-hexadecane	n-octadecane	n-octacosane
0	.0000	.0000	.0000	.0000	.0000	.0000	.0000
500	.0502	.0444	.0400	.0353	.1413[e]		
1,000	.0835	.0751	.0683	.0609	.1576		
1,500	.1073	.0982	.0902	.0787[d]	.1676		
2,000	.1266	.1170	.1079		.1756		
2,500	.1428	.1326	.1228	.1869	.1823	.0479	.0437
3,000	.1567	.1460	.1359		.1887		
3,500	.1688	.1579	[c]		.1951		
4,000	.1796	.1686			.2006		
4,500	.1893	.1782			.2056		
5,000	.1982	.1868[b]	.2319	.2158	.2096	.0777	.0719
10,000	.2659[a]	.2941	.2694	.2516	.2446	.1183	.1117
15,000	.3394	.3205	.2948	.2769	.2696	.1470	.1407
20,000	.3616	.3398	.3141	.2961	.2883	.1695	.1637
25,000	.3789	.3546	.3293	.3115	.3034	.1886	.1829
30,000	.3937	.3669	.3418	.3244	.3156	.2051	.1992
35,000	.4057	.3775	.3524	.3359	.3261	.2196	.2128
40,000	.4163	.3872	.3615	.3464	.3352	.2324	.2239

a Freezes at 11,450. $\Delta V/V_0$ .2782 and .3202
b Freezes at 5,510. $\Delta V/V_0$ .1863 and .2475
c Freezes at 3,050. $\Delta V/V_0$ .1370 and .2107
d Freezes at 1,700. $\Delta V/V_0$ .0839 and .1869
e Freezes at 420. $\Delta V/V_0$ .0300 and .1392 $\Delta V/V_0$ = .0192 at 250 and .1498 at 750

table exhibits definite regularities. The first five of the series are liquid at atmospheric pressure at room temperature, and are brought to freeze by the application of pressure. The pressure required for freezing decreases as the number of carbons in the chain increases. A plot of the freezing pressure against number of carbons yields a smooth curve, rising very rapidly at the lower end. The fractional discontinuities of volume on freezing are 0.0420, 0.0612, 0.0737, 0.1030, and 0.1092. If these values are plotted against number of carbons a curve rising with increase of carbon number will be obtained, but the curve is not smooth. A very considerable part of the rise with increasing carbon number is to be ascribed, not to an effect of structure, but to

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the incidental effect of decreasing freezing pressure, since the volume discontinuity of nearly every substance increases as the freezing pressure is lowered. The initial compressibility in the liquid phase decreases as the number of carbons increases, as shown, for example, by the row of compressions for 500 kg/cm². This is in large part a reflecrion of the greater volatility of the lighter members of the series. The effect persists over the entire range, the compressions at 40,000 showing the same sequence. The initial effects reflecting the proximity of the critical point with the vapor might be expected to be wiped out at the upper end of the pressure range, where other sorts of structural effect might be expected to begin to become apparent. As a rough indication of this, the relative compression in the last 20,000 kg/cm² may be taken, that is the difference between the rows for 20,000 and for 40,000 kg/cm² in the table. The numerical values for the seven members of the series are respectively: 0.0547, 0.0474, 0.0474, 0.0503, 0.0469, 0.0629, and 0.0602. The tendency of the first five, for the paraffins initially liquid, is an irregular decrease with increasing carbon number. The last two, for those members initially solid, are on the average 25 per cent higher than the others. Part of this is to be ascribed to the fact that the initial V_0 on which the compressions are calculated is the volume of the solid rather than the larger initial volume of the liquid. However, not as much as half of the difference can be explained in this way, the difference of volume between solid and liquid at the atmospheric freezing point not being much over 10 per cent. Taking due account of this factor, there seems to be no outstanding regularity left in the compressions at the upper end of the pressure range. This means that other factors become more important than the simple size of the molecule.

In Table II are collected the compressions of the other 23 hydrocarbons. The arrangement is by number of carbons in the molecule. This means that substances initially liquid occupy the first part of the table and those initially solid the last part, with some overlapping toward the center. Obvious factors which might be taken into account in searching for correlations with the compressions are: the carbon-hydrogen ratio in the molecule, the ratio of the number of double bonds between carbons to single bonds between carbons and the type of molecular structure, whether straight chain, single ring, or double ring. Search has disclosed no obvious correlation between any of these factors and the initial compressibility, the total compression under 40,000 kg/cm², or the compression in the last 20,000 kg/cm². There are, however, certain gross regularities in the behavior of the hydrocarbons as a group. The total compression under 40,000 kg/cm² for those substances initially solid clusters around 0.2, ranging from a

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TABLE II

COMPRESSION OF MISCELLANEOUS HYDROCARBONS

Pressure kg/cm²	$\Delta V/V_0$										
	Amylene	Benzene	Cyclo-hexane	Methyl Cyclo-hexane	Styrene	o-xylene	m-xylene	p-xylene	Cap-rylene	Cumene	Mesi-tylene
0	.0000	.0000	.0000[b]	.0000	.0000	.0000	.0000	.0000[h]	.0000[i]	.0000[j]	.0000
500	.0642	[a]	.0812	.0353	.0316	.0321	.0352		.0458	.0348	.0333
1,000	.1016		.1021	.0637	.0544	.0561	.0602		.0763	.0593	.0572
1,500	.1288		.1179	.0862	.0728	.0748	.0802		.0988	.0788	.0756
2,000	.1500		.1302	.1042	.0884	.0902	.0968		.1174	.0950	.0914
2,500	.1672	.1992	.1420	.1196	.1017	[f]	.1109	.2243	.1331	.1087	.1053
3,000	.1818		.1526	.1332	.1136[e]		.1236		.1467	.1207	.1177
3,500	.1946		.1622	.1452			.1350		.1587	.1315	{.1290[k]
4,000	.2060		.1719	.1558			.1452		.1691	.1413	{.1629
4,500	.2162		.1809	.1655			.1543		.1782	.1503	
5,000	.2255	.2314	.1880	.1745	.1942	.2029	{.1624	.2503	.1867	.1586	.1817
			[c]				{.2117				
10,000		.2731	.272	.2308	.2362	.2396	{.2211[g]	.2820	.2419	.2135	.2299
				[d]			{.2461				
15,000		.3007	.298	.2663	.2638	.2643	.2721	.3054	.2779	.2488	.2615
20,000		.3217	.318	.2910	.2842	.2832	.2919	.3230	.3041	.2738	.2827
25,000		.3385	.334	.3106	.3002	.2992	.3077	.3370	.3241	.2928	.2990
30,000		.3526	.348	.3266	.3136	.3112	.3209	.3485	.3400	.3076	.3123
35,000		.3659	.359	.3401	.3253	.3212	.3323	.3582	.3532	.3196	.3240
40,000		.3758	.369	.3516	.3355	.3298	.3425	.3666	.3649	.3294	.3345

a Freezes at 680. $\Delta V/V_0$ .0634 and .1596
b Freezes at 355. $\Delta V/V_0$ .0326 and .0742. $(\Delta V/V_0)_{liq.}$ = .0233 at 250
c Transition at 7,500. $\Delta V/V_0$ 0.216 and 0.257
d See text
e Freezes at 3,120. $\Delta V/V_0$ .1162 and .1647
f Freezes at 2,300. $\Delta V/V_0$ .0983 and .1690
g Freezes in this region. Upper figures for liquid, lower for solid.
h Freezes at 343. $\Delta V/V_0$ .0249 and .1889
i Liquid throughout
j Liquid throughout
k Freezes at 3,500

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TABLE II (*Continued*)

COMPRESSION OF MISCELLANEOUS HYDROCARBONS

Pressure kg/cm²	$\Delta V/V_0$											
	Naphthalene	Tetrahydronaphthalene	Dipentene	3-methyl naphthalene	Acenaphthene	Diphenyl	Fluorene	Anthracene	Dibenzyl	Fluoranthene	Hexaethyl benzene	Triphenyl Methane
0	.0000[l]	.0000	.0000[n]	.0000[o]	.0000[o]	.0000[o]	.0000[o]	.0000[o]	.0000[o]	.0000[o]	.0000[o]	.0000[o]
500		.0249	.0339									
1,000		.0447	.0583									
1,500		.0608	.0773									
2,000		.0745	.0930									
2,500	.0364	.0866	.1066	.0483	.0338	.0429	.0373	.0305	.0457	.0373	.0361	.0354
3,000		.0974	.1187									
3,500		[m]	.1294									
4,000			.1389									
4,500			.1473									
5,000	.0636	.1763	.1549	.0780	.0568	.0705	.0615	.0539	.0772	.0615	.0617	.0601
10,000	.1021	.2106	.2085	.1190	.0899	.1086	.0974	.0876	.1219	.0974	.0984	.0956
15,000	.1295	.2359	.2434	.1483	.1149	.1361	.1247	.1132	.1521	.1247	.1254	.1225
20,000	.1513	.2546	.2669	.1713	.1346	.1574	.1464	.1336	.1747	.1464	.1465	.1444
25,000	.1698	.2695	.2832	.1905	.1507	.1753	.1649	.1509	.1929	.1649	.1645	.1627
30,000	.1858	.2822	.2966	.2067	.1648	.1905	.1803	.1657	.2086	.1803	.1809[p] / .1909	.1781
35,000	.1996	.2937	.3083	.2206	.1776	.2035	.1937	.1792	.2223	.1937	.2072	.1912
40,000	.2114	.3041	.3188	.2325	.1893	.2146	.2055	.1911	.2343	.2055		.2025

l Solid throughout
m Freezes at 3,050. $\Delta V/V_0$ .0984 and .1599
n Liquid throughout
o Solid throughout
p Sluggish transition here, not complete

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minimum of 0.189 for acenaphthene to a maximum of 0.234 for dibenzyl. The solid normal paraffins also fall within the same range. For hydrocarbons initially liquid, on the other hand, the total compression under 40,000 kg cm², including in this the volume change on freezing, ranges from a minimum of 0.304 for tetrahydronaphthalene to a maximum of 0.416 for n-heptane. Included in this range are the three liquids which are not forced to freeze by the maximum pressure, namely caprylene, cumene and dipentene. It is probable that the non-freezing of these liquids is a subcooling effect, accentuated by imperfect purity. The fact that the compressions at 40,000 of those substances which remain liquid are not materially different from those which have passed from the liquid to the solid phase means that sufficiently high pressures force the liquid into approximately the same volume as the crystal lattice. Or expressed differently, the volume of a glass is not greatly different from that of the corresponding crystal.

TABLE III

COMPRESSION OF MISCELLANEOUS NON-HYDROCARBONS

Pressure kg/cm²	$\Delta V/V_0$							
	Methylene chloride	Chloroform	Ethylene bromide	Ethyl acetate	Chlorobenzene	n-amyl ether	Fluorocarbons	
							light	oil
0	.0000	.0000	.0000	.0000*d*	.0000	.0000	.0000	.0000
500	.0400	.0404	.0267*c*	.0446	.0311	.0401	.0703	.0275
1,000	.0683	.0682		.0739	.0543	.0681	.1070	.0493
1,500	.0905	.0900		.0956	.0729	.0890	.1322	.0672
2,000	.1087	.1081		.1136	.0885	.1062	.1517	.0819
2,500	.1241	.1236	.1752	.1291	.1022	.1211	.1680	.0939
3,000	.1375	.1368		.1427	.1141	.1342	.1820	.1040
3,500	.1494	.1484		.1547	.1247	.1457	.1945	.1127
4,000	.1601	.1588		.1654	.1344	.1558	*g*	.1200
4,500	.1698	.1682		.1750	.1434	.1649		.1261
5,000	.1787	.1767*b*	.2059	.1838	.1517*e*	.1731	.2475	.1312
10,000	.2393	.2834	.2479	.2413	.2303	.2304*f*	.2914	
15,000	.3152*a*	.3090	.2759	.2781	.2574	.2828	.3134	
20,000	.3388	.3287	.2969	.3032	.2776	.3030	.3293	
25,000	.3563	.3439	.3163	.3221	.2937	.3202	.3416	
30,000	.3702	.3571	.3273	.3371	.3066	.3352	.3511	
35,000	.3811	.3690	.3386	.3501	.3173	.3484	.3589	
40,000	.3898	.3798	.3481	.3621	.3264	.3602	.3653	

a Freezes at 12,440. $\Delta V/V_0$ .2586 and .2987
b Freezes at 5,500. $\Delta V/V_0$ .1850 and .2524
c Freezes at 650. $\Delta V/V_0$ .0333 and .1300
d Liquid throughout
e Freezes at 7,500. $\Delta V/V_0$ .1828 and .2121
f Freezes at 11,140. $\Delta V/V_0$ .2241 and .2451
g Freezes at 4,400. $\Delta V/V_0$ .2139 and .2391

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Of the substances in Table II, special comment in addition to that already made in the discussion of previous measurement, is required for methylcyclohexane. In addition to the figures in the table which pertain to the liquid phase, an isolated point was obtained for the solid phase at 12,440 kg/cm². At this pressure, $\Delta V/V_0$ for the solid was 0.2707 and for the liquid 0.2506. Methylcyclohexane is one of the rare substances, of which only one example has been found before,[20] which do not experience a change of phase on the initial application of pressures in excess of the pressure of thermodynamic equilibrium. If pressure is maintained for a considerable time far beyond the equilibrium pressure, some process of nucleus formation slowly occurs in the liquid, so that when pressure is released to a point sufficiently close to the equilibrium pressure, solidification occurs with a paradoxical decrease of volume.

In Table III are collected the results for the eight miscellaneous organic compounds. The general character of the numerical results is the same as that in Tables I and II. In other words, introducing other atoms beside hydrogen and carbon into the molecule has not produced any spectacular changes in the compressions. The abnormally high initial compressibility of the light fluorocarbon is to be no-

TABLE IV

COMPRESSION OF DI-METHYL SILOXANE POLYMERS

Pressure kg/cm²	$\Delta V/V_0$						
	Dimer	Trimer	Tetra-mer	Penta-mer	Hexa-mer	Hepta-mer	Octa-mer
0	.0000	.0000[b]	.0000[b]	.0000[b]	.0000[b]	.0000[b]	.0000[b]
500	.0586	.0568	.0531	.0532	.0485	.0496	.0456
1,000	.0960	.0921	.0864	.0862	.0800	.0818	.0780
1,500	.1227	.1174	.1110	.1102	.1039	.1055	.1012
2,000	.1434	.1373	.1308	.1291	.1231	.1245	.1200
2,500	.1603	.1539	.1470	.1450	.1393	.1403	.1357
3,000	.1752	.1679	.1609	.1587	.1530	.1539	.1492
3,500	.1882[a]	.1800	.1730	.1707	.1647	.1659	.1611
4,000		.1908	.1838	.1813	.1751	.1766	.1719
4,500		.2007	.1936	.1909	.1847	.1862	.1813
5,000	.2518	.2099	.2026	.1996	.1937	.1947	.1898
10,000	.2928	.2736	.2590	.2559	.2498	.2514	.2486
15,000	.3184	.3096	.2933	.2895	.2865	.2831	.2790
20,000	.3384	.3332	.3149	.3113	.3052	.3051	.3000
25,000	.3546	.3508	.3310	.3272	.3212	.3215	.3163
30,000	.3679	.3650	.3442	.3403	.3347	.3350	.3298
35,000	.3797	.3774	.3555	.3525	.3470	.3467	.3414
40,000	.3905	.3886	.3660	.3637	.3583	.3570	.3515

a Freezes at 3.790. $\Delta V/V_0$ .1952 and .2315

b Liquid throughout

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ticed, the largest of any measured here. At 40,000, however, the volume compression of methylene chloride has overtaken it; the obvious reason is its larger change of volume on freezing.

In Table IV are given the compressions of the di-methyl siloxane polymers, and in Table V the similar Dow Corning fluids. The

TABLE V

COMPRESSION OF "DOW-CORNING FLUIDS"

Pressure kg/cm²	$\Delta V/V_0$								
	500–0.65	500–1.00	500–2.00	500–12.8	200–100	200–350	200–1,000	200–12,500	550–112
0	.0000	.0000[b]	.0000[b]	.0000[b]	.0000[b]	.0000[b]	.0000[b]	.0000[b]	.0000[b]
500	.0634	.0536	.0485	.0447	.0449	.0447	.0458	.0446	.0305
1,000	.1004	.0884	.0821	.0729	.0734	.0742	.0736	.0729	.0512
1,500	.1259	.1139	.1069	.0949	.0946	.0955	.0947	.0933	.0675
2,000	.1462	.1341	.1267	.1131	.1120	.1128	.1123	.1104	.0813
2,500	.1633	.1508	.1434	.1285	.1271	.1278	.1274	.1253	.0934
3,000	.1782	.1651	.1579	.1416	.1402	.1411	.1403	.1384	.1043
3,500	.1916	.1776	.1705	.1531	.1519	.1526	.1517	.1500	.1143
4,000	[a]	.1884	.1817	.1633	.1620	.1627	.1618	.1602	.1235
4,500		.1979	.1917	.1726	.1711	.1716	.1705	.1690	.1320
5,000	.2571	.2066	.2007	.1813	.1793	.1796	.1787	.1771	.1399
10,000	.2970	.2633	.2604	.2367	.2349	.2374	.2324	.2304	.1785
15,000	.3244	.2960	.2949	.2689	.2652	.2676	.2615	.2594	.2083
20,000	.3442	.3170	.3151	.2906	.2863	.2888	.2820	.2808	.2305
25,000	.3594	.3328	.3308	.3076	.3032	.3056	.2990	.2980	.2480
30,000	.3720	.3457	.3456	.3214	.3173	.3294	.3131	.3125	.2632
35,000	.3827	.3566	.3577	.3329	.3294	.3410	.3249	.3246	.2765
40,000	.3921	.3658	.3689	.3429	.3404	.3519	.3349	.3350	.2889

a Freezes at 4,010. $\Delta V/V_0$ .2044 and .2404
b Liquid throughout

polymers, through the octamer, fall within the range of the other liquids measured in this paper, but are among the more compressible of them. The compression in general diminishes with increasing molecular weight. The curve of compression against molecular weight is, however, not smooth but alternates, the compression of the odd polymers being above a smooth curve through the even members. This is evident from a glance at the row of compressions for 500 kg/cm² or for 40,000. The amplitude of oscillation from even to odd is less at the higher pressures, as might be expected.

The only pure liquid brought to freeze by pressure is the dimer. This is distinctly not what might be expected, but the higher members of the series would be expected to have progressively lower freezing pressures, as for example, in the series of normal paraffins. The reason for the failure of the higher members to freeze under pressure

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should be investigated further. It may possibly be connected with inadequate chemical purity, but it seems more likely that it is connected with the abnormally rapid increase of viscosity of these liquids under pressure, an effect which would facilitate subcooling because of the difficulty of nucleus formation.

The Dow Corning fluids show the same progression that would be expected from the pure polymers, carried somewhat further, since the more viscous members of the series contain polymers much higher than the octamer. The same failure to freeze under pressure except for the first member of the series, is shown here as was shown by the pure polymers. With indefinitely great increase of viscosity, that is, with indefinite increase of length of the polymeric chain, the compression appears to approach an asymptotic value. This again is what might be expected. It is obvious that the mechanism responsible for viscosity must be entirely different from that responsible for compression.

The single example of a Dow Corning fluid of the 550 series is distinctly less compressible than the others, corresponding to its radically different structure.

Finally, if the results of this paper be compared with the results for the organic compounds in a previous paper over the same pressure range,[1] a general parallelism will be found. In the former paper there are, however, a considerable number of examples of smaller compressions. The organic compounds of this paper, especially the hydrocarbons, do not include examples of as close binding as frequently occur in organic compounds.

LYMAN LABORATORY OF PHYSICS,
Harvard University, Cambridge, Mass.

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THE ANALOGOUS SHAPES OF CELLS AND BUBBLES

By Frederic T. Lewis

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By Frederic T. Lewis

Harvard Medical School, Boston, Massachusetts

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Introduction

In the slow movement toward presenting fundamental biological forms on a physical and mathematical basis, recent studies of cell shape play an important part. Among the forces which determine the forms of cells whether solitary or in contact with one another, Sir D'Arcy Thompson finds that "surface tension is certainly of great, and is probably of paramount importance."[1] But the surface tension of several types of simple cells has been measured and found very low—"of the order of 0.1 to 1.0 dyne per cm."[2] Indeed it is supplemented by other surface forces, viz. "an elastic tension which may be a function of the cell-membrane thickness, and an elastic tension in the cortical gel layer of the cell," so that Danielli, whom we quote, finds that "the solution of most of the problems of cell form is at least some way beyond our immediate grasp." The existence of cilia, which Professor Thompson regards as "*sui generis;* we know nothing of them from the physical side," leads Danielli to comment that they are "in frank contradiction to a belief in any kind of dominant role for surface tension forces."

Soap bubbles, solitary or in collocation, with which cells from earliest times have been compared, are conformed (according to

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Thompson) by surface tension "in the absence (to all intents and purposes) of alien forces from the field." Matzke, who has provided unique and valuable data on the three-dimensional shape of soap bubbles in foam, dissents, asserting that "other forces such as adhesion and gravity are still present."[3] Instead of ascribing bubble shape to surface tension, he uses the more general term "surface forces" for the controlling factor. He finds that the bubbles are of such diverse shapes that although significant average numbers of facets can be demonstrated, "no one combination among those found could be considered the type"—"Kelvin's ideal figure is not achieved."[4]

So also, in the long and growing series of statistical studies of cell shape in unspecialized plant tissues, by Dr. Matzke or under his direction,[5] it is consistently held that "none of the combinations found was clearly predominant, and none is interpreted as 'the type'." His statistics are unquestionably accurate, and his preparations which fail to show the Kelvin pattern, fail also to show any substitute type. To conclude from such data that there is no type is to retreat from a position supposedly gained toward the mathematical and physical interpretation of cell forms. Before conceding the loss, it is here proposed to review the basis for accepting the Kelvin pattern as the typical shape both of bubbles and of cells. In regard to type cells, our point of view is precisely that of Jeffries Wyman in his "Notes on the Cells of the Bee" (1866). After enumerating eight "marked variations" in honeycomb, he comments:[6]

> In view of the frequency of such variations, however near the bee may come to a typical cell in the construction of its comb, it may be reasonably doubted whether a type cell is ever made. Here, as is so often the case elsewhere in nature, the type-form is an ideal one, and, with this, real forms seldom or never coincide. Even in crystallography, where the forms are essentially geometrical, we are told that 'natural crystals are always more or less distorted or imperfect,' and that 'the science of crystallography could never have been developed from observation alone.'

Typical Shape of the Initial Cell and Bubble

It is agreed that cells are primarily spherical. The human ovum, the yolk of a hen's egg, and the oösphere of the rockweed *Fucus* are familiar examples. Their form is due to the geometrical properties of space, and to surface forces tending to reduce their surface area to a minimum, both factors being indispensable and "paramount." If cubes had less surface per volume than spheres the initial cells would be cubical.

The property of liquids that causes them "to draw together into a shape which makes the surface area, and therefore the potential

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energy, least for a given volume" is a form of molecular attraction known as surface tension.[7] But in all geometrical solids, considered as configurations of points in space, the internal points of the configuration in their relation to one another differ from those on the surface. Hence the mathematical contention that "the interior of a sphere is a solid, while the configuration consisting of that interior and the sphere, *i. e.* the sperical surface, is not a solid."[8] Similarly the internal molecules in a drop of pure water have been distinguished from those on the surface, which have a surface tension of 75 dynes per cm. In the initial cell, which for all its complexity is still a liquid drop, the outer layers, multiple and reinforced, become visible as a cell membrane. Ectoplasm is set off from endoplasm, ectoderm covers entoderm, as is inherent in a geometric solid.

The initial soap bubble is a liquid drop with a central cavity. The film that forms its wall is commonly described as composed of three layers, viz. an outer and an inner surface layer, simple or stratified (both being in contact with the air and hence similar in structure) between which there is a middle layer, more or less developed, having no free surface. Thus the bubble is comparable with a coelenterate or a blastodermic vesicle rather than with an ordinary single cell, for their walls also consist of three layers,—ectoderm, entoderm, and intervening mesoderm. Although in bubbles of glass the existence of special layers has been denied, the wall of a hollow sphere inherently tends toward tripartite subdivision.

By optical and electrical methods the thinnest soap-bubble film has been calculated to be not more than 60Å thick (.006 μ)—too thin for direct microscopic observation of its layers. At that thinness the soap film has been figured diagrammatically as composed of two monomolecular surface layers of normally oriented soap molecules, held together by intervening liquid.[9] An ordinary soap film is much thicker, and Perrin has described it as formed of many laminae or identical leaflets, superimposed like the layers in mica, making the thickness of the entire film at any point an integral multiple of that of the primary leaflet.[10] This does not provide a middle layer such as Willard Gibbs assumed in describing the contact between a vertical soap film and a horizontal plate of glass. He wrote:[11]

> At such an edge (where a soap film meets a glass plate at right angles) we generally find a liquid mass, continuous in phase with the interior of the film, which is bounded by concave surfaces, and in which pressure is therefore less than in the interior of the film. This liquid mass therefore exerts a strong suction upon the interior of the film, by which its thickness is rapidly reduced.

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The layers in a contact of that sort can readily be detected with a hand lens, and may be prepared for study as follows. Using the soap solution recommended by Matzke[3]—triethanolamine oleate 7.5 g., glycerin 34 g., and distilled water 58.5 g.—and employing his method of blowing measured bubbles, a bubble containing 0.5 cc. of air may be brought into contact with a large cover-glass. It at once becomes detached from the nozzle of the syringe and forms a hemispherical bubble with no perceptible change in volume, attached to the glass by a "Gibbs ring." The cover and bubble can then be inverted and placed on the stage of the microscope, conveniently supported by a blackened block of wood, ½ inch thick, through which a 1-inch hole has been bored.

Under a 16-mm. objective the circle of attachment of the bubble to the under side of the cover-glass appears as a broad band subdivided into an outer, a middle, and an inner layer. A small portion of such a ring is shown at *o*, *m*, *i*, in Figure 1C. The middle layer is a light band containing particles in motion, being a portion of the "liquid mass continuous in phase with the interior of the film" (Gibbs). The wider outer and inner bands are flaring black expansions of the corresponding layers of the bubble film. The inner layer invisibly covers the glass within the hemispheric bubble, and the outer spreads upon the glass in the opposite direction. Perpendicular to the plane of the cover-glass, this Gibbs ring rapidly becomes thin and passes out of focus.

Certain optical reflections and diffractions complicate the picture. The light middle layer may appear split into several parallel strands. Both the outer and the inner dark layers regularly show a light line, usually toward their free margin, which differs in nature from the light middle layer. Since these light lines (photographed in Figure 1) vary from brilliance to extinction on rotating the preparation in reflected light, and shift their position with oblique illumination, they presumably are not structural laminae.

The Paired Bubble and Cluster of Three

When two equal spherical drops of water, or of soap solution, are brought together, they unite in a single spherical drop with a loss in surface area of 20.6 per cent. A similar union, initiated when two 3-layered bubbles come in contact, is checked when their outer surface layers have been reduced by 16 per cent. As inferred from what is seen in Gibbs rings, the process of partial fusion involves a disintegration of their outer layers, beginning at the initial point of contact, and spreading over the entire circular contact area. Within the

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circle, molecules of the disorganized outer layers may be added to the liquid middle layer, but at its circumference the outer layer of one bubble maintains unbroken continuity with that of the other. Since the inner surface layers do not come in contact, they show no reduction. On the contrary they are stretched, and increase in area, presumably by incorporating molecules from the middle layer, until they have grown by approximately 5 per cent. When the area of the reduced outer layers is to that of the increased inner layers as 4 to 5, the bubbles come to rest in a characteristic pattern figured by Thompson,[1] ('42, p. 473), who discusses it geometrically as if the bubble walls were single layers. The pattern is that made by two circles of equal radius which overlap by half the length of the radius: the overlapping arcs are then replaced by their common chord which represents the septum.

A precisely similar pattern is formed by the Gibbs rings of two hemispherical bubbles of equal size, immediately upon coming into mutual contact when deposited on a glass plate. Figure 1A is a photograph of one end of the septum, vertically oriented, as it joins the convex bubble walls. It is seen that the septum has acquired the structure and thinness of the outer walls, and since all three exert equal tensions, they (or their tangents) meet at angles of 120°. The tension of the septum checks the coalescence of the bubbles when their net loss of surface is limited to 5.5 per cent.

When a third bubble of the same volume is brought into contact with the septate pair, it may form a straight or bent chain of three. If, however, it crosses or merely impinges upon the end of the septum between the pair, the group at once becomes a trefoil cluster, bounded (on the glass plate) by three semicircles of equal radius ($r = 1.0$). From the three points of junction of these semicircles, septa of equal length ($\sqrt{4/3}$) converge to a central vertex, meeting at angles of 120°. The axial structure which they form upon the glass is photographed in Figure 1B.

Thus the contact of a third bubble across the notch at the top of Figure 1A, and the consequent disintegration of the contiguous outer layers, has converted the outer bubble walls into septa, the two new ones being structurally identical with the first one, and under the same tension. At their distal ends they meet the tangents of the outer bubble walls at angles of 120°, duplicating the pattern of Figure 1A. A continuous outer layer invests the entire cluster, having a surface area 25.7 per cent less than those of three separate equal bubbles of the same total volume. The inner surface areas are increased by 6.7 per cent, so that the three bubbles in becoming a trefoil cluster

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reduce their total surface by 9.5 per cent—4 per cent more than was accomplished by the pair, which accounts for their pattern. Tension of the septa prevents further reduction. The three spherical segments appear to be nearer three-quarters of an entire sphere (74.1%) than "approximately five-sevenths" as recorded by Dewar[12] and later, perhaps not independently, by Thompson.

The axial structure in the trefoil cluster is a triangular-prismatic space filled with soap solution, into which the liquid middle layer of the septal walls drains, as described by Gibbs. Such triangular spaces (triangular in cross section) are always found where three bubbles meet. They follow all the edges of the polyhedral bubbles throughout a foam; and since they are not rings, they have been called "edge canals." They drain the "interfacial spaces" occupied by the middle layer of the bubble walls, and in turn they empty into tetrahedral "corner cavities" where four bubbles meet. If the cluster of bubbles rests on a glass plate, the plate, against which the soap films flare, serve as the third bubble enclosing a canal, or a fourth one at a corner.

The same configuration is found in certain metal alloys, resulting "from an attempted approach to equilibrium between phase and grain interfaces whose surface tensions geometrically balance each other at the points and along the lines where they meet."[13] Not only are there "drawings of cells in both elder pith and human fat that a metallurgist would immediately accept as sketches of isolated metal grains," but liquid lead in relation with grains of copper may present the pattern of triangular-prismatic edge canals and tetrahedral corner cavities as described both for cells and for soap bubbles (see C. S. Smith,[13] fig. 18).

There are several features of the photographs (Fig. 1) which the writer is unable to explain. The edge canals become very slender before entering the corner cavities—so fine that they are difficult to detect and may sometimes be occluded. Within the *peripheral* corner cavities (Fig. 1A) the soap solution is generally gray, whereas in a *central* cavity (Fig. 1B), which is at the end of a vertical axial column of the solution, it is yellow. Yet it was unexpected that the contents of such cavities would photograph as black and white respectively, both in diffuse and polarized light. The cavities show a refractive lining; and tension in the curved liquid-crystalline films which form their walls produces a transverse line, with a more or less distinct marginal notch at either end, that bisects the wall of the cavity in a node-like manner. On either side of this "node" there is a pale nodule, perceptible in ordinary light though obscure in photographs, which becomes conspicuous in polarized light (Fig. 1D). Some of these features have striking cellular analogies.

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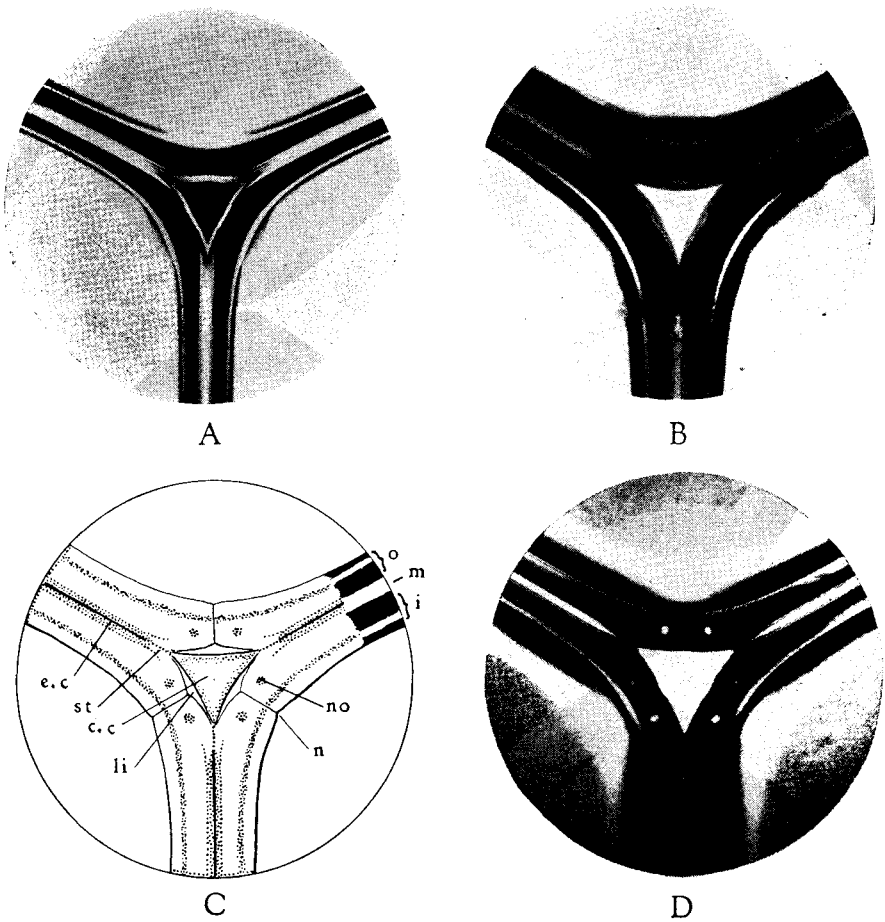

FIGURE 1. A. Portion of the walls of a conjoined pair of bubbles adherent to the under side of a cover glass, through which they were photographed. The triangular accumulation of soap solution is where the convexly horizontal walls of the pair join their vertical septum. B. Like A except that a 3rd bubble has come into contact with the horizontal arms of A, converting them into septa: the triangle is now the center of a trefoil cluster. C. Labels for photographs A, B, and D—*o*, *m*, and *i*, outer, middle, and inner layers of the bubble wall; *c. c*, corner cavity; *e. c*, edge canal; *li*, lining of corner cavity; *n*, node; *no*, nodule; *st*, strait, or slender connection of the edge canal with the corner cavity. D. Like B, but with polarized light and crossed Nicols. All photographs × 35.

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The Paired Cell and Cluster of Three

Unlike liquid drops or paired bubbles which by coalescence or partial coalescence reduce their surface as a result of surface tension, the mammalium ovum segments into a pair of cells with increased surface. Cell division always increases the surface area, and with associated changes in cell shape it constitutes a third basic factor in the form of cells. If a spherical nucleus divides in halves into two spherical nuclei, the surface area is increased in the ratio of 1 to $\sqrt[3]{2}$ or by 25.99 per cent, but unless cell walls are formed we have only binucleate or multinucleate cells. If a spherical cell becomes bisected by a septum which provides a septal surface for each hemisphere, the increase in surface would be 50 per cent. This, however, is materially reduced through the concurrent effect of surface forces. Nevertheless, division differs radically from "the liberation of surface energy which takes place spontaneously whenever two droplets meet: to break one droplet into two, we have to supply energy from outside."[14]

Although Bütschli's tentative suggestion, in 1876, that after nuclear division an *increased* surface tension in the equatorial region causes the cell to divide[15] has been favorably received, Robertson[16] argued that for division there must be an equatorial *diminution* of surface tension. Both postulates are faulty, but the title of Robertson's paper—"Note on the Chemical Mechanics of Cell Division"—and the simple experiment which he described as follows, may prove highly significant:—

> If, now, a drop of olive oil which is not too large (about 2 to 3 mm. diameter) be floated on a layer of water, and a thread saturated in N/10 alkali (NaOH, KOH) be brought gently in contact with a diameter of the drop, the almost immediate effect is the division of the drop into two.

Various oils may be used. A drop of cottonseed oil spreads on the surface of water as a thin film. A second drop in the midst of the film forms an ellipsoid, and when a cotton thread soaked in a solution of caustic soda is applied to the ellipsoid, the drop breaks into two or more fragments, which shoot apart as if by mutual repulsion. Having come to rest as round droplets, some of the fragments may then reunite through surface tension. It has been said that during the division of the ovum, the two new parts tend to repel each other after the division is finished.[17] The disruptive force in this experiment is associated with the formation of soap, and Robertson, in 1909, thought it "possible that cholin, set free in nuclein synthesis, brings about in a similar manner, the division of the cell through the forma-

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tion of soaps in the equatorial planes." Four years later he conceded that there was no valid evidence in support of that idea.[18]

The simplest cell membrane in animal cells is described as a fatty or oily layer—a lipoid-containing pellicle—invisible or scarcely visible with the microscope.[19] It soon undergoes a triple subdivision by the development of a middle layer of intercellular substance between the membranes of adjacent cells. In plants also, according to I. W. Bailey,[20] the cell wall is "actually a three-layered structure composed of two modified, cellulose-containing primary walls and a truly isotropic intercellular layer." In both animal and plants the middle layer is a product, formed between the cells, whereas in bubbles it is the formative material itself—the soap solution—which exists throughout the film that bounds the initial bubble.

The coherent pair of cells formed when the mammalian ovum divides in two differs from the conjoined pair of bubbles by having a deep notch between its halves. Studies of living ova by Warren Lewis and his associates have shown that this is not the compressing effect of the encapsulating zona pellucida. "The pressure of the zona may play a role, but a very minor one if any."[21] The notch between the cells is not crossed by a continuous outer film as in the bubbles photographed in Figure 1A. No such conjoining film is seen in photographs of the 2-cell stage of mice and rabbits, and none could be found in the corresponding preparations of the pig's ova, made by Dr. C. H. Heuser, which the writer was privileged to examine.[22]

Similarly the trefoil cluster of cells bears only a general resemblance to that of bubbles. It is a pattern duplicated by the agglutination of three egg yolks freed from the whites, which are in fact single food-laden cells. There is a triangular space between them as in Figure 1B, but it is larger and empty of cell substance: the tripartite adhesion walls are shorter, so that a greater portion of each sphere remains free. Yet the cell and bubble trefoils are comparable in their symmetry.

Euler's Theorem in Relation to the Paired and Trefoil Clusters

The famous and important proposition[23] that "in every solid bounded by plane surfaces the number of solid angles plus the number of surfaces exceeds the number of edges by 2," may freely be extended to an endless variety of biological shapes with surfaces variously curved. It applies to the pea-pod, whether it be considered as having 2 angles, 2 surfaces and 2 edges, or, as a folded leaf, it presents 2 angles, 1 surface and 1 edge. If indeed it were pendent and pyriform, with 1 angle, 1 surface, and no edges, the pervasive theorem would

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still apply. The spherical ovum, lacking a meridian connecting two poles which would relate it to one of the pea-pod shapes, and unless it is considered a polyhedron with an infinite number of facets, is an exception. So also is the paired bubble unless the circumference of its circular interface be regarded either as uniangular, at some point having its beginning and end, or as a polygon having an infinite number of sides. The trefoil cluster, however, with no axial interspace, conforms both as a whole, and in its three segments separately: —all have 2 angles, 3 surfaces and 3 edges. In foams and tissues, all the many-faceted shapes assumed are subject to Euler's law.

Three Possible Arrangements of Four Cells

"This subject has hitherto been wholly neglected," Schleiden wrote in 1845, "though it must form the foundation of the whole science of morphology."[24] When four new cells arise, as he explained with a diagram, they may be either in a row linearly; or, two and two beside each other, they may spread in a plane; or one may be centered above a trefoil cluster composed of the other three, and initiate a solid. It will be a long time, Schleiden thought, before we can account satisfactorily for the production of these diverse arrangements, and it must suffice to have called attention to their "durchgreifende Wichtigkeit" ("paramount importance," in Lankester's translation). Cell shape is determined accordingly. In linear series, as in the stamen hairs of Tradescantia, the cells form filaments; in single layers, which are next to be considered, they produce membranes; and in superimposed layers or in masses, they yield parenchyma.

The Shape of Cells and Bubbles in Single Layers

Turpin[25] in 1829, groping toward the cell theory, pictured spherical vesicles arranged in a layer, as becoming hexagonal by mutual pressure, and as forming 14-hedra in masses. As cells, his 14-hedra are incorrect and unstackable, but there are significant features in his simple figure of the alga *Bichatia vesiculinosa*, Turpin (now *Gloeocapsa coracina*, Kützing) which he failed to record. In outline his drawing is reproduced as Figure 2A, showing 12 cells that form a single layer.

Such one-layered clusters, unless composed of few cells or those in a double row, consist of central cells and peripheral cells. The central cells have two free surfaces (above and below respectively) and a varying number of lateral contacts with those around them. Each free surface and lateral contact produces a polygonal facet whereby the sphere becomes a polyhedron. Peripheral cells or bubbles, if the single-layered cluster is suspended in fluid or floating in air, have only one free surface. Bubbles especially tend to be arranged in *compact*

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clusters, so that, for example, when 4 are in contact with a 5th, the 4 will form a continuous row and will not occur isolated or divided into groups.

When a single layer of cells or bubbles is wholly free, and when, as with bubbles under Plateau's law, all vertices are 3-rayed and all corner-angles trihedral, the total number of facets (F) of all the cells or bubbles in a compact layer may be expressed in a simple formula. If nc is the number of central cells, and np the number of peripheral cells, then

$$F = 8nc + 5np - 6$$

The numerals placed in Figure 2A indicate the number of facets of the individual cells. In accordance with the formula, a layer of cells can not consist only of octahedral central and pentahedral peripheral cells, or of those averaging 8 and 5 facets respectively; there must be a few deviations to provide the deduction of 6 facets. In Figure 2A this is accomplished by 6 tetrahedral peripheral cells. The deviation, however, may occur partly or sometimes wholly in the central cells.

The total number of sides of the polygonal facets that cover a single free layer of bubbles or cells taken as a whole, above, below, and over its outer margin, is also regulated. Thus the layer in Figure 2A presents external facets of two shapes. The central cells are hexagonal above and below, and the apparent pentagons of the three pentahedral cells, when continued to the under side of the layer, are also found to be hexagons. The free surface of the six tetrahedral cells, when so continued, remains 4-sided. Every vertex in this group is 3-rayed. If four edges met at a vertex, it is readily seen that two adjacent polygons would each lose a side; 4 sides would be lost for every 5-rayed vertex, and so on. Then, if S is the number of sides of the polygons covering a layer, and n is the number of facets they enclose, with v_4 the number of 4-rayed vertices, v_5 the number of 5-rayed, etc.,

$$S = 6\,(n - 2) - 2v_4 - 4v_5 \text{ etc.}$$

Ordinarily 4-rayed vertices are infrequent, or, as in Figure 2A, altogether absent, and the formula then means merely that the polygons covering the layer have 12 fewer sides than if they were all hexagons. Its importance lies in the fact that it applies not only to the polygons covering layers and masses of cells, but also to those which cover individual cells, where tetrahedral angles form the 4-rayed vertices. In testing this formula by the peripheral cells in Figure 2A, it will be found that they all have two 2-sided facets, each bounded by an arc and its chord.

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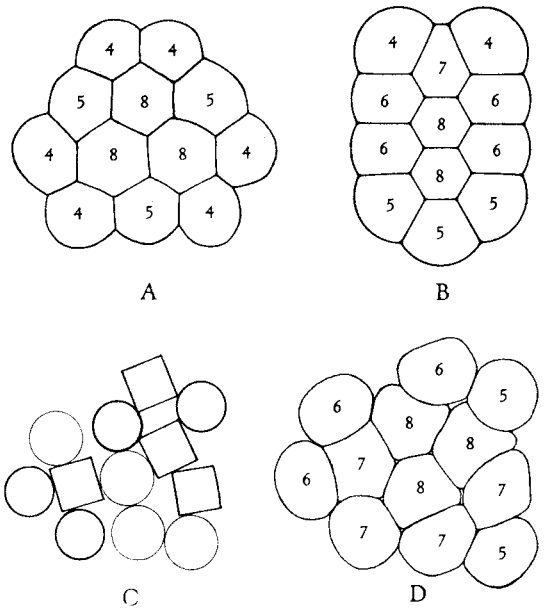

FIGURE 2. A. Single layer of 12 cells outlined from Turpin's drawing of Bichatia (1829). The numerals are the numbers of facets of the cells when the layer is free from a substratum. B. Layer of 12 bubbles (½ cc.) adherent to a glass plate. Photograph, to which the numbers of facets of the adherent bubbles have been added. C. Arrangement of 12 plasticine bodies of equal volume—cubes, cylinders and spheres—which on compression between 2 glass plates yielded the pattern D. The facets added to these bodies by both plates are included in the numerals in D.

The foregoing exacting requirements as to the number and shape of the facets presented by cells in a single free layer can be met by averages of very diverse forms, or by the prevalent occurrence of the few typical shapes. Thus if the 3 central 8-hedra in Figure 2A should divide in halves in the planes of apothems, the resulting layer of 15 cells might contain no central 8-hedron, but, with lowered average number of facets for the central cells, the entire layer would still comply with the formula. The same would be true if the peripheral cells divided, raising the average facets of the central cells, or if, as commonly happens, both kinds divide. Free layers composed of many cells thus maintain the general average of 8 facets for central cells and 5 facets for peripheral cells, with the required deduction of 6 facets per

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layer. The 5-faceted form of the peripheral cell is that which would result from bisection of a central cell in the plane of an apothem and the merging of the division plane with the bisected top and basal facets in a single free surface.

In a layer of bubbles there is no division, and therefore the typical shapes may be freely presented. It is easy to make a compact layer of 100 bubbles with 60, or somewhat more, central bubbles all of the typical 8-hedral form—the only shape that can occur uniformly under the specified conditions.

Single layers of bubbles upon a glass plate present cell-like patterns, but with a precision rarely approached in cells (Fig. 2B). Against the glass every peripheral bubble adds a basal facet; whereas the number and shape of facets of the central bubbles remain unaltered. Hence the facet formula becomes $F = 8nc + 6np - 6$, as exemplified by the numerals in Figure 2B. The formula for the number of sides of the polygons covering the layer, $S = 6(n - 2) - 2v_4$, applies without change. In the cluster figured there are 10 peripheral bubbles with 10 4-rayed vertices, formed where any two adjacent free surfaces meet the two corresponding basal surfaces—all 4 at one point.

If the 13th bubble is added along the side of the cluster of 12 in Figure 2B, it promptly takes the 4-faceted form shown at the top of the photograph, quite like that of a member of an isolated trefoil group. Another bubble of the same volume placed beside it would cause it to become 5-faceted, like the three at the bottom of the figure. These in turn become 6- and 7-faceted through added contacts, the heptagonal bubbles being characteristically stretched out by retaining a narrow lateral connection with the film investing the entire cluster. When the lateral free surface is lost, usually by adding another bubble to the layer at that point, the peripheral bubble retracts as a central octahedron. Occasionally the adjacent tetrahedra meet across the top, converting the peripheral heptahedron into a central pentagonal prism, which remains heptahedral. Although a regular pentagonal prism of a certain height has less surface area per volume than any other plane-faced geometrical solid with 7 faces, the inclusion of a pentagonal bubble among the central hexagons necessarily increases the average surface area.

Of the plane-faced bodies of equal volume which can be mutually conjoined to form a single layer without interstices and which have single free surfaces above and below, hexagonal prisms, in height equal to the apothems of their terminal regular hexagons, present the least possible surface. When the volume of such a prism is 1.0, the length of the sides of the terminal hexagon is $\sqrt[3]{2/9}$ or .60571 and the area

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of the hexagon is .95318; the height of the prism is 1.04912. The "surface index" of this minimal hexagonal prism, or its surface area divided by that of a sphere of equal volume is 1.1826.

The greater surface of the minimal pentagonal prism of equal volume (nearly 1.6 per cent) is indicated by its index 1.2015. It does not at all fit into a mosaic of minimal hexagonal prisms since its sides are longer, the area of its terminal polygon is greater, and its height is shorter than that of the hexagonal type (Table I). It can

TABLE I

REGULAR RIGHT PRISMS OF EQUAL VOLUME ($V = 1.0$) AND LEAST SURFACE

End Polygons			Height of Prism	Surface Index S/Σ
Number of Sides	Length of Sides	Area of Polygon		
4	1.0000	1.0000	1.0000	1.2407
5	.7502	.9684	1.0326	1.2015
6	.6057	.9532	1.0491	1.1826
7	.5098	.9446	1.0587	1.1719
8	.4410	.9392	1.0648	1.1653

be incorporated in the layer of hexagonal prisms only by deviations which further increase its surface, or that of the adjacent prisms, in varying proportions.

It is necessary, however, from our corollary of Euler's theorem, that with the pentagonal bubbles an equal number of heptagonal forms be introduced, provided that the central bubbles are limited to these 3 shapes and that the added facets are not, wholly or in part, relegated to the peripheral layer. The minimal heptagonal prism, with an index of 1.1719, has 0.9 per cent less surface area than the minimal hexagonal prisms of the same volume. For voulme 1.0, the sides of the heptagon are shorter than those of the hexagon; its area is less; and the height of the prism is consequently greater. The diminished surface area of this minimal heptagonal prism would be partly offset by the deviations required to fit it with other bubbles in the layer, but even if it could be fully retained, the introduction of a minimal pentagonal prism matched by a minimal heptagonal prism would cause a net increase in surface area over that of 2 minimal hexagonal prisms of 0.35 per cent.

A similar increase in area would result from including minimal prismatic bubbles of more than 7 sides, although their own areas

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diminish with every added side. Thus the presence of a minimal octagonal prism, with 1.46 per cent less surface than the minimal hexagonal prism of the same volume, would cause a net addition to the surface area, whether balanced by a minimal quadrilateral prism (a cube) or by 2 pentagonal prisms. Bubbles may readily be induced to depart from their typical minimal shapes and to come to rest in diverse irregular patterns of greater surface, which they maintain with considerable stability.

Unexpectedly it is found easier to produce a central pentagonal bubble with its increased surface than to form a central heptagonal bubble with decreased surface. This may be because the pentagonal prism of a certain height has the least possible surface for a 7 plane-faced polyhedron, whereas the heptagonal prism is not the form with least surface for the 9-faced. If, however, a cluster of 19 bubbles of equal volume is made upon a glass plate, consisting of a central bubble surrounded by an inner circuit of 6, and enclosed by an outer circuit of 12 (an arrangement shown by the heavily outlined bubbles in Figure 4), and if then the central bubble is broken, the entire cluster immediately readjusts itself and fills the gap. The remaining 6 central bubbles frequently form 2 pentagonal, 2 hexagonal and 2 heptagonal prisms, or sometimes 3 pentagonal and 3 heptagonal, the perimeters and areas of which may be measured in photographs similar to Figure 2B.

It is found that the hexagonal prisms have become irregular, with longer sides against the pentagonal prisms and shorter sides against the heptagonal, as would be expected from Table I. Although the average length of side of the pentagonal bubble is greater than that of the hexagonal, which in turn is greater than that of the heptagonal, the differences shown in the table have been reduced so that the relative areas of the polygons have been reversed. The average areas of the central polygons are found to vary directly with their number of sides.

In explanation it may be said that the sides or septa of the bubbles, being alike in structure and in tension, tend to meet at angles of 120°, for only at that angle can each septum be the equilibrant of the other two and all equilibrants equal. Hence the central bubbles tend to become regular hexagons in cross section, with an area determined by 6 equal contractile forces acting upon the contained air. When pentagonal in section, with average internal angles of 108°, the resultant contractile tensions of the 5 septa forming the pentagon exceed the stretching force of the 5 septa attached to its exterior, and the cross-sectional area becomes smaller. In heptagonal bubbles, with

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average internal angles of 128°, the stretching tension exceeds the contracting, and the 7-sided bubbles are larger in section than the 6-sided. But in the peripheral bubbles all internal angles approach 120°—the contractile force is proportional to their number—and their areas of contact with the glass vary inversely with their number of sides (Fig. 2B).

An important feature of the prismatic central bubbles conjoined in a single layer is the dome with which each of them is capped. If this dome were a portion of the sphere within which the corresponding minimal flat-faced hexagonal prism is inscribed, the conditions outlined in Figure 3 could result. Figure 3A represents the cross section of the upper end of the hexagonal shaft of the domed prism within a small circle of the circumscribing sphere, at the level *c-d* of Figure 3B.

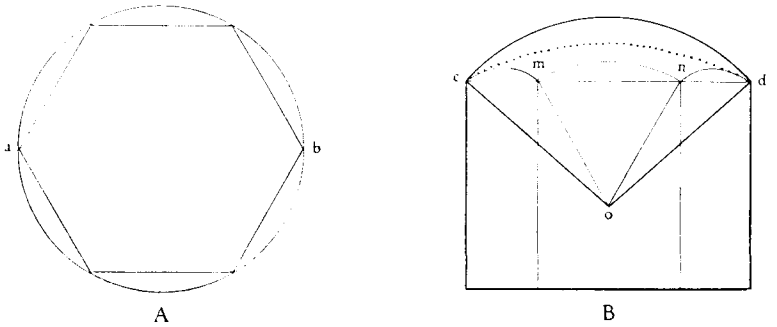

FIGURE 3. B. Vertical projection of a hexagonal prism with domed top derived from the circumscribing sphere. Its radius *oc* is $\sqrt{1\frac{3}{4}}$ when the side of the hexagon is 1.0. The prism is considered to retain the volume and cross sectional area of the minimal hexagonal prism by reducing the length of the shaft. A. Cross section of B at the level *cmnd* showing in the horizontal plane 6 segments of the inscribing circle lost by truncation. Vertically, in B, these truncations are bounded by arcs like *mn* which extend the lateral facets of the prism, having radius *om* = 1.0, in the planes of the lateral facets. The dotted arc *cd* shows the height of a cap derived from a sphere of radius 2.0, subtended by a central angle of 60°.

Figure 3B is a vertical projection of that prism with its dome derived from the circumscribing sphere, being a portion of the spherical segment of one base subtended by a central angle, *c o d*, of 98° 12′ 47″.

The domed prism in 3B, as a central bubble resting on glass, would have less surface area than the form which bubbles actually assume, but it is incompatible with an equal tension in the vertical walls and the tangents of the dome. Consequently, with increased surface, the

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curve of the dome is reduced to that of a spherical segment subtended by a cone with apical angle of 60°. The radius of the sphere which provides the rounded cap is then twice the length of the sides of the hexagon. If the vertical circular segments remain as before (i. e. like the arc *m-n* in Fig. 3B) the tangents of all three domes which meet at a vertex in the hexagonal mosaic would form angles of 120° with the vertical edges of the prism. I am indebted to Mr. William A. Pierce for suggesting this combination, which is tentatively presented as the typical shape of central bubbles in a single layer when resting on a glass plate. The free surface is no longer a portion of a simple spherical segment, but is a modification, the area of which has not yet been determined.

Epidermal cells resting on a basement membrane may present comparable forms. Over the tall prismatic cells in the cucumber, low domes have been found, appearing like segments from spheres of radius 3.86 times the length of the hexagonal side, thus being subtended by cones of 30°. From calculations made by Graustein[26] it may be reckoned that such a low dome would reduce the surface index of a minimal hexagonal cell from 1.1826 to 1.1606. Higher domes would reduce it more, but tension appears to check this reduction when the subtending angles are 60°.

The Shape of Solids Compressed in a Single Layer

"There is no doubt but that solids possess surface energy and that the only reason that this does not manifest itself more clearly as a surface tension is that solids do not possess sufficient mobility."[27] Matzke,[3] conceding that surface forces are "of relatively greater importance in the bubbles" than in lead shot—that they are "more effectively significant in the soap film system than in the lead shot system"—does not exclude them altogether from a share in shaping compressed solids. Yet the deformation of plastic solids by an external force, whereby their surface area is increased, contravenes the effect of whatever surface tensions such bodies possess. Radical differences in the resulting forms may therefore be expected.

Twelve plasticine cubes of different colors were made with ½ inch edges; four of them were rolled into spherical form, and four into cylinders ½ inch tall, all being therefore of the same volume. They were placed haphazard on a glass plate, except that they were near enough together so that each was in contact with at least one other (Fig. 2C). A glass plate was placed over them, and in a screw press the distance between the parallel plates was reduced to ¼ inch.

During compression the cubes lost the sharpness of their peripheral angles which were disregarded in counting the facets for Figure 2D.

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The interfacial layer of air, corresponding somewhat with intercellular substance, is pressed out from between the plasticine surfaces which, except for color differences, would blend indistinguishably. Several triangular edge canals are seen in Figure 2D, and two quadrilateral spaces. Another turn of the press would reduce the canals to 3-rayed vertices, and the quadrilateral spaces would become small facets in the direction of their long axes. In numbering the facets in the figure, these spaces have been considered as already eliminated. Pressure from the glass plate above and below provides, or preserves, a top and basal facet for all the plasticine bodies, and assuming that any 4-rayed vertex appearing in Figure 2D extends from the top to the basal surface, the formula now becomes

$$F = 8nc + 7np - 6 - 2v_4$$

The same formula would apply to the layer of bubbles if it were in contact with plates both above and below. Compliance does not depend on the uniform size of the bodies. If, for example, around the central octahedral body in Figure 2D the quadrilateral and the four triangular spaces should be occupied by very small cells, 6- and 5-faceted respectively, thereby adding facets to the surrounding bodies, the formula would still apply.

Features of the layer of plasticine bodies incompatible with dominant surface tension are (1) the existence of angles and edges over the free surface; (2) the frequent approach to 4-rayed vertices and their occasional formation (apart from those at the peripheral contacts with the glass plate); and (3) the marked irregularity of the polygonal areas in the central mosaic. Yet the layer of space-filling compressed solids is necessarily divided into central and peripheral bodies governed by the same formula for the number of facets as the layer of bubbles. This compliance depends on the prevalence of trihedral corners and 3-rayed vertices in both cases. In a free layer of bubbles vertices with more than 3 rays are eliminated by surface tension. For compressed solids the chances are heavily against the meeting of 4 or more compressed or enlarging bodies at a mathematical point.

The Shape of Bubbles in a Double Layer

The double layer of hexagonal cells in honeycomb which vegetable cells resemble sufficiently to account for their name *cells*, is readily seen to present a very different pattern from that of a double layer of bubbles. The typical cell in honeycomb is closed below by 3 rhombic facets, yet Müllenhoff[28] ventured to consider the work of the bees as a surface tension effect upon fluid wax! Vogt[29] refuted this

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sufficiently; but Thompson reaffirms his belief that "we have to do with a true tension effect . . . in the first few cells of a wasp's comb we recognize the identical configurations exhibited . . . by a group of 3 or 4 soap bubbles." Soap bubbles in double layers never assume the form of cells in honeycomb, which have tetrahedral angles contrary to Plateau's law; nor do bee's cells provide the least possible surface for their volume. The saving in wax by a 4-faceted base of the bubble type, though definite, would be trivial, as verified by preliminary calculations for which the writer is indebted to Dr. R. F. Arens. So slight is the advantage in the perfect form that *bubbles* commonly depart from it.

When a fourth bubble is placed on top of a trefoil cluster, it becomes centered over the axial depression and acquires a 3-faceted base. If, however, the bubble is deposited over any similar 3-rayed vertex on the upper surface of a single layer of bubbles of equal volume, it does not remain there, but spreads to cover two vertices, or often three. Its base becomes 4- or 5-faceted. Further additions which develop a top layer produce a sheet of upper bubbles in which those surrounded by others will show, as found by Matzke,[3] "normally one hexagonal face above, in addition to 6 lateral contacts and 4 basal ones." That defines their type.

There is only one pattern of that description which can occur throughout both strata of a double layer (except at their periphery). Its production requires an orderly arrangement of the bubbles which is not produced by "blowing air through a soap solution" (Desch[30]), or by heaping bubbles of uniform volume in a cylindrical dish until they fill it, which was Matzke's better method. Over the floor of the chosen dish, bubbles of uniform volume, but varying in number, may form a continuous single layer, in which every peripheral bubble has a basal and a vertical facet against the glass and a free upper surface. Thus the total number of facets of the bubbles in that layer (as with the plasticine bodies) is $8nc + 7np - 6$. A bubble placed upon it to start a second layer is liable to be drawn down to the glass and added to the basal layer, sometimes as a quadrilateral bubble balanced by two adjacent heptagons, which cannot reduce the combined surface area (cf. Table I). Some pentagonal and heptagonal bubbles are sure to be introduced, and yet there will be a basal layer complying with the foregoing formula. In a dish full of bubbles, as seen in Matzke's photograph, the horizontal stratification and the orientation established by the basal layer tend to be preserved throughout the mass.

To avoid the effects of adhesion to the sides of the dish, 19 bubbles ($\frac{1}{2}$ cc.) were deposited in a compact cluster on a glass plate, and 4

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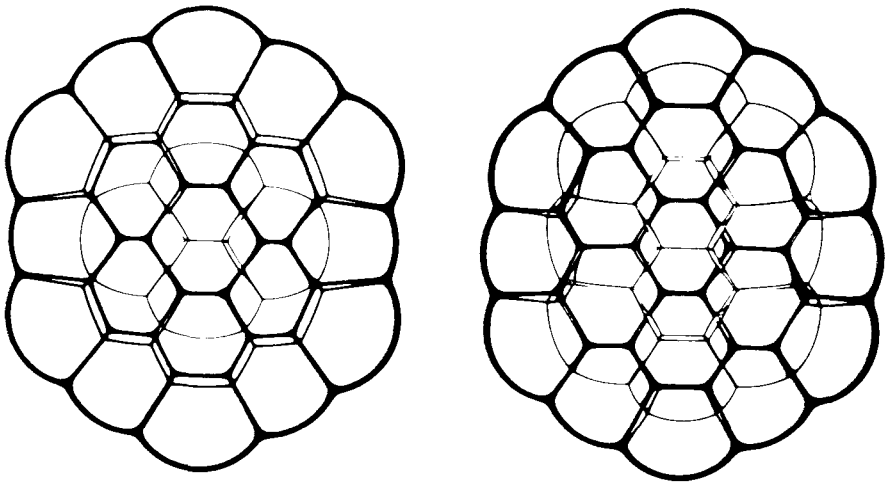
bubbles of the same volume were placed above them in a second layer. In the photograph, Figure 4A, these upper bubbles are sharply but thinly outlined against the heavy edge canals of those below. Each of these bubbles has 4 basal facets exactly matched by upper facets in the basal layer. The heavily outlined central bubble of the basal group has acquired the typical shape which all but the peripheral bubbles in a duplex layer could exhibit uniformly. It is still a hexagonal prism, but 2 quadrilateral and 2 hexagonal facets have replaced the former upper surface, converting the octahedron into an 11-hedron.



A B

FIGURE 4. A. Cluster of 4 bubbles, lightly outlined, all with 4-faceted bases, resting on a basal layer of 19. The central basal bubble is a typical 11-hedron of formula 4Q–4P–3H. B. Six bubbles have been added to the upper layer in A: the 2 central upper, and 3 of the central lower, are typical 11-hedra.—Unretouched photographs of ½ cc. bubbles, × 1¼.

Two of the 6 lateral facets of the prism, opposite each other, have remained quardilateral, and the other four have become pentagonal. The eleventh facet is the hexagon against the glass plate. As a whole this bubble, having 4 quadrilateral, 4 pentagonal and 3 hexagonal facets (formula 4–4–3) has the pattern of a bisected Kelvin 14-hedron.

Before the overlying bubbles were deposited, the outline of the central basal bubble was a *regular* hexagon (as in Fig. 2B). Now it shows an interesting approximation to the irregular hexagon characteristic of certain bisections of Kelvin's orthic tetrakaidecahedron,

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described by Grautsein and Matzke[31] as having two short sides of length a, four long sides of length $\sqrt{3}\,a$, internal angles between two long sides of 109° 28′ 16″, and between a long and a short side of 125° 15′ 52″, with an area of $4\sqrt{2}\,a^2$.

In Figure 4B six bubbles have been added to the upper layer in A, making two more typical 11-hedra in the lower layer, and two in the upper. Further additions in linear series could increase their number indefinitely, yet it seldom happens. As seen in Figure 5A–D, in which a lower layer of 10 bubbles presents 10 vertices to be covered by an upper layer, the production of the Kelvin pattern is not readily accomplished. It requires an upper layer of 7 bubbles (Fig. 5A) to cover the 10 vertices, and 4 upper bubbles must temporarily remain with 3 basal facets. Much more often the successively added bubbles

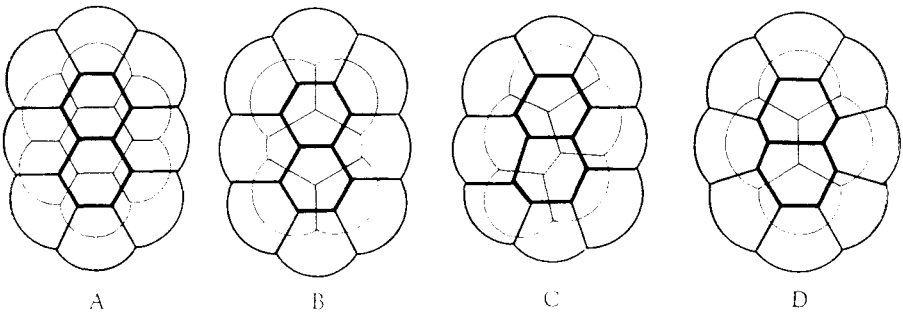

FIGURE 5. A–D. Four observed arrangements of bubbles in an upper layer placed upon a uniform basal layer of 10 bubbles, with 10 corners to be covered. Drawings (not photographs).

acquire at once a 4-faceted base (Fig. 5C), sometimes 5-faceted (Fig. 5D), with great consequent irregularity. Frequently (Fig. 5B, C, D) the basal bubbles end above in 3 pentagonal facets.

Furthermore, since a regular basal layer provides only 2 vertices apiece for similar bubbles of equal volume in an upper layer, the appropriation of 3 vertices by certain early arrivals there either reduces the number of overlying bubbles which cover all the vertices (Fig. 5D), or forces some of the upper bubbles to form 3-faceted bases. An upper bubble with a base of 3 pentagonal facets (not shown in Fig. 5) would be like the 2 central basal bubbles in 5B, merely overturned. They form less readily in the upper layer, where the bubbles glide freely over those below, than in the lower layer attached to the glass. Since it is a shape which cannot occur uniformly throughout a layer, occasional 10-hedral bubbles of that sort may be regarded as deviations from the 11-hedral type.

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The Shape of Bubbles in Multiple Layers

On attempting to start a third layer by placing a bubble over the center of the upper layer in Figure 4B, the additional bubble generally wedges its way down into the second layer which it helps to make irregular. Confining the lower layers within a cylindrical dish does not prevent this result. The bottom of a circular dish 46 mm. in diameter may be completely covered by 19 bubbles (½ cc.) arranged like the basal layer in Figure 4. Five more bubbles placed upon it may be drawn down into that layer as would never happen with vegetable cells, in which gliding movements are so generally denied. Upon this variable foundation second and third layers are deposited,

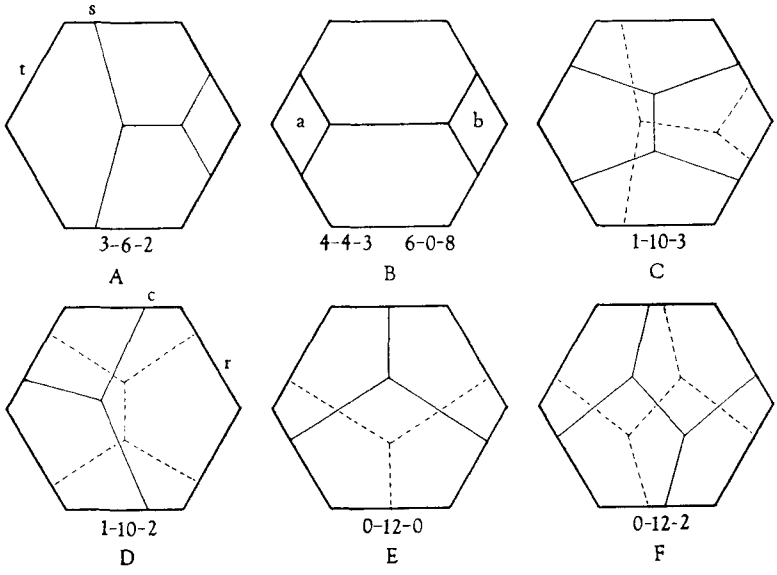

Figure 6. Diagrams of bubble shapes, oriented as hexagonal prisms, with top facets bounded by unbroken lines and basal facets marked out by dashes. The lateral facets are hexagonal when a side of the prism is met by 2 edges; pentagonal when met by one; and quadrilateral when the side remains free. A is an inverted peripheral bubble with its free hexagonal facet below, and its upturned basal end above, deviating from the typical peripheral pattern, 4–4–3, shown in B. By considering the top and basal facets in B as identical and superimposed, B represents also the 14-hedron (6–0–8), with deviations in C–F. F has 2 lateral hexagonal facets, toward the letters C and F respectively: bisection of one of them along an apothem yields the 0–12–3 combination:—of both, the 0–12–4.

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also varying in their number of bubbles, with consequent inevitable irregularity. Very skillfully and thoroughly these forms have been pictured by Matzke,[3] both for peripheral bubbles, 400 of which had an average of 10.99 facets, and for central bubbles, where, for 600, he reported an average of 13.7 facets. No complete layer was tabulated, which from his photographed figure 1 would include approximately 150 bubbles. Two circuits "at least" of bubbles immediately beneath the peripheral layer were excluded from his tabulation.

The relation of the shapes which Matzke found most often to Kelvin's mathematical pattern is summarized in the diagram, Figure 6. The peripheral bubble, whether at the top of the full jar or on the sides against the glass, is expected to be the bisected 14-hedral form already described. It has 11 facets (Fig. 6B), its free surface being hexagonal, its lateral surfaces quadrilateral (two of them) and pentagonal (the other 4), and its 4-faceted base combining 2 hexagons and 2 quadrilaterals. The total facets of each polygonal shape, in the order of their number of sides beginning with the smallest, make convenient formulas for such patterns, and for this peripheral bubble it is 4–4–3. Matzke found 22 examples in 400.

In what may be regarded as a deviation, one of the basal quadrilateral facets may be enlarged at the expense of the hexagons. Facet *a* of Figure 6B could thus become the basal hegaxon of Figure 6A, or in a lesser deviation the septum *s* might terminate at *t*. The different patterns which result are both within the formula 3–6–2. Since either the quadrilateral *a* or *b* of Figure 6B may be the one to enlarge, and either its upper or its lower side may be the one to remain relatively fixed, the resulting combinations of facets occur in inverted and mirror image forms. Including all its varieties Matzke found 3–6–2 "the commonest of the 43 combinations of facets"—67 of them in 400 peripheral bubbles. The 11-hedral bubble in the basal layer of Figure 5C is an example of this shape in a setting which illustrates its origin.

Just as the bisected Kelvin 14-hedron is the expected form for the peripheral bubble, in which it is frequently realized and where its number of facets is the average actually found, the entire Kelvin 14-hedron is expected for the central bubbles, with an average of 14 facets for the deviations. The slight requisite deduction of 12 facets per layer, $F = 14nc + 11np - 12$, which may be either in the peripheral or the central bubbles,[32] could hardly be recognized in statistical studies of bubbles taken at random from the deep part of layers of many members. For 600 central bubbles Matzke[3] reports an average of 13.7 facets and finds that "the deviation from 14 is apparently not

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without meaning." Of the Kelvin 14-hedral pattern "with 8 hexagonal and 6 quadrilateral facets" he saw "not a single one." What he has recorded in his unique and important study may be summarized as follows.

For the Kelvin 14-hedron the diagram Figure 6B serves without change, since its lower and upper facets, in this orientation, duplicate one another and may be considered superimposed. It has no pentagonal facets, and its formula is 6–0–8. If on its upper surface the quadrilateral facets *a* and *b* should enlarge until they met in a common vertical edge, a top of 4 pentagonal facets would result. Such a top over a base produced as in Figure 6A would make the irregular bubble 1–10–3 (Fig. 6C). With 73 examples in 600, Matzke found this the most common form of 14-hedral bubbles. A top of 4 pentagons may be produced on the central hexagonal bubble in a cluster of 7 by adding an upper layer of 4 bubbles in opposite pairs, 2 with 4-faceted bases and 2 with 3-faceted. One pair of the upper bubbles will form a common septum over the central bubble beneath. When, as in Figure 4A, that septum overlies a maximum diameter of the basal hexagon, the typical pattern results; but *over an apothem* it produces 4 pentagons.

A 4-faceted end above or below with a 3-faceted opposite end, often arising in the confusion of securing 4-faceted bases by unoriented bubbles (cf. Fig. 5), accounts for several forms with 13 facets which are included in Matzke's tabulation:—4–4–5 (4 bubbles); 3–6–4 (36 bubbles); 2–8–3 (19 bubbles); and 1–10–2 (Fig. 6D), by far the commonest arrangement of all, 118 examples. Its irregular 3-faceted top would arise if facet *b* (Fig. 6B) had enlarged to a hexagon and facet *a* been forced out of the picture. Another pattern of the 1–10–2 combination occurs when the edge *c* (Fig. 6D) is moved to *r*. The 3-faceted and 4-faceted ends may then become quite symmetrical.

When regular 3-faceted ends occur at both ends of a central hexagonal bubble, their pentagonal facets may be superimposed forming a 3–6–3 combination, or they may alternate (Fig. 6E) forming a more or less regular dodecahedron. In a haphazard distribution the 3–6–3 form should occur with the greater frequency, but it is indeed significant that Matzke found 50 pentagonal 12-hedra for 7 of the 3–6–3 pattern.

Of special importance is the 0–12–2 combination (Fig. 6F) produced by terminations of 4 pentagonal facets each, alternately oriented. If superimposed, these ends form one of the common 2–8–4 patterns (64 examples). Alternately oriented, and with all facets regular,

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ERRATUM

In the Proceedings, Vol. 77, No. 5, p. 173, Table II, under "Q P H" in column 5, for 0–21–1 read 0–12–1.

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they yield, as Goldberg demonstrated, a polyhedron with less surface area than any other plane-faced 14-hedron of equal volume.

In a mathematical paper of great biological interest[33] Goldberg has shown that for convex polyhedra of the least surface for their volume—i. e., for the "best" polyhedra—pentagonal facets are introduced with the 7-hedron which has 2; and that their number of pentagons increases by 2 with every added facet up to the 12-hedron with 12, beyond which the number of effective pentagons cannot be increased. With Steinitz, Goldberg defines "the number $K = S^3/V^2$ where S is the surface area and V the volume of the polyhedron: then the 'best' polyhedra are those which have the smallest value of K." He finds that K for the pentagonal dodecahedron is 149.87; for the orthic 14-hedron of the same volume, 150.12: and for the 14-hedron (0–12–2) "formed by truncating the two apices of a double skew pyramid," 143.94. Matzke counted 39 bubbles of that last combination in 600.

How greatly the bubble shapes differ from those of cells is shown in Table II, derived from Matzke's statistics. It records the number

TABLE II

NUMBERS OF POLYHEDRAL BUBBLES IN 600, COMPRESSED SHOT IN 624, AND CELLS IN 550, HAVING EITHER 10 OR 12 PENTAGONAL FACETS. COMPILED FROM MATZKE'S DATA

Q P H	Bubbles	Shot	Cells	Q P H	Bubbles	Shot	Cells
1–10–6	0	0	0	0–12–4	10	0	0
1–10–5	4	0	0	0–12–3	21	1	0
1–10–4	35	3	1	0–12–2	39	2	0
1–10–3	73	3	1	0–21–1	—	–	–
1–10–2	118	5	1	0–12–0	50	3	0

of bubbles in 600, of compressed shot in 624, and of undifferentiated vegetable cells in 550, having the number of quadrilateral, pentagonal, and hexagonal facets listed in the columns Q, P, and H, respectively. The combination 0–12–1 is geometrically impossible. The division of one of the lateral hexagons in Figure 6F, along an apothem, into a pair of pentagons can occur by its coming in contact with 2 bubbles, each covering 3 vertices. This would convert the 0–12–2 combination into 0–12–3, and such a division involving both lateral hexagons of the 0–12–2 would produce the 0–12–4 pattern. In geometrically perfect form the K of that 16-hedron becomes 139.2 (Goldberg).

None of the bubble shapes with less surface than the Kelvin 14-hedron can be stacked uniformly to fill space. They must occur in a

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variety of approximations, all of them involving an increase in their own surface area, and preventing the most effective reduction possible in the uniform Kelvin layer. It has not been shown that through irregularity anything "better" has been accomplished *for the mass as a whole*, than by regularity and the mathematical solution. On the contrary it is found that in the single layer of hexagonal prismatic bubbles, stable deviations from the type are frequent, and they involve an increase in surface. In a most careful study of the volumes and surface areas of *models* of 100 plant cells—a method which may be inadequate for such slight differences as would be presented—Marvin[34] has published data which fail to show a reduction in surface area proportional to the number of pentagonal facets, although such a reduction is quite possible. His figures indicate that the irregular cells average 4 per cent more surface than orthic 14-hedra of the same volume when compared cell by cell.

The average of 13.70 facets for the central bubbles, described by Matzke as "close to 14 faces," is not as close as may actually occur in entire layers. The typical central bubble is certainly not a 13-hedron —much less a regular dodecahedron—but a geometrical form which, under the dominant surface tension of bubbles, is subject to a series of deviations which Matzke has been the first to tabulate.

The Typical Shape of Undifferentiated Cells in Masses and in Surface Layers

From Matzke's data it is seen that a bubble within foam has an average of 9.17 pentagonal facets. This contrasts with compressed shot in which, as shown by Marvin, the average shot has 5.48 pentagonal facets. Undifferentiated cells resemble the shot, with an average of 5.32 pentagonal facets per cell. That does not differ appreciably from the number produced by truncating the 6 tetrahedral angles of a rhombic dodecahedron in all possible combinations of 3 planes at right angles: 729 polyhedra result, with an average of precisely 14 facets, and an average of $5\frac{1}{3}$ pentagonal facets per polyhedron.[35] These figures are sufficient to show that although bubbles with their paramount surface tension have a large excess of pentagonal facets, such facets occur commonly in all space-filling masses of polyhedra unless specially arranged to prevent them. Since no single form of polyhedron with pentagonal facets can uniformly fill space, either these bodies—bubbles, compressed shot, and cells—have no typical shape, as concluded from the Columbia studies, or the pentagonal facets occur in deviations from, or approximations toward, some typical shape which is geometrically possible.

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There are two geometrical shapes which uniformly fill space without interstices and can provide hexagonal cross sections comparable with those in Figure 2. With 6 lateral surfaces in both cases, there may be 3 facets above and below (with edges from the central apex to *alternate angles* of the hexagon) forming rhombic 12-hedra; or there may be 4 facets above and below, as already described, forming orthic 14-hedra, with 58/100 of 1 per cent less surface than the 12-hedra. Misled by Buffon's experiment with peas and by the form of honeycomb, Kieser, in 1815, declared that as determined both by mathematical laws and by observation, the basic form of cells "must be" the rhombic dodecahedron.[36] That the basic shape is Kelvin's minimal tetrakaidecahedron is shown by the following considerations.

The average number of facets of central cells is found to be close to 14. In 7 simple tissues studied by 5 investigators, Matzke tabulates the average for 700 cells as 13.86 facets. By including 100 cells which have been reported by the writer and 200 later recorded by Hulbary, the average for 1000 cells becomes 13.95. There are several sources of error, so that this result is not inconsistent with an average of 14 facets for central cells. A slight downward deviation is expected from the occasional occurrence of tetrahedral angles, and may well be present from other causes, but the data leave no doubt that the average central cell is a 14-hedron.

The average number of facets of peripheral or epidermal cells, when in relation with underlying cells of the same diameter should therefore approach 11, with the bisected 14-hedron, of formula 4–4–3 as the type (Fig. 7). Realization of this shape depends on finding epidermal cells of the same average area in cross section as the cells underneath. Usually the subepidermal cells are larger, as in the two plant tissues first selected. In the cucumber, tall prismatic epidermal cells stand upon supporting cells measuring approximately 3 times their area in cross section, the cells in both layers presenting more or less regular hexagonal outlines. Consequently the geometrical pattern which such epidermal cells approach consists of 10-faceted and 8-faceted cells in the proportion of 2 to 1, reducing the average number of facets of the epidermal cells from 11 to $9\frac{1}{3}$ (Lewis[37]). The very different epidermis covering Tradescantia stems consists of rod-shaped cells, 12 times as long as they are wide, placed lengthwise of the stem. They rest on cells of the same width and general shape, but 3 times as long. The epidermal pattern here differs from that in the cucumber by consisting of 10-faceted and *9-faceted* cells in the proportion of 2 to 1, making the average facets $9\frac{2}{3}$ (Lewis[38]). It was noted, however, that with supporting cells twice the length of the epidermal (and

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hence of twice their area in section) the latter would average 3 basal facets instead of 4. Thus they would average 10 facets instead of 11; their typical formula would be 4–4–2.

Matzke recently reported[39] that in Anacharis "the average number of facets for 200 epidermal cells was 10.005," and that the "commonest combination (4–4–2) was found in 34 cells." The subepidermal cells

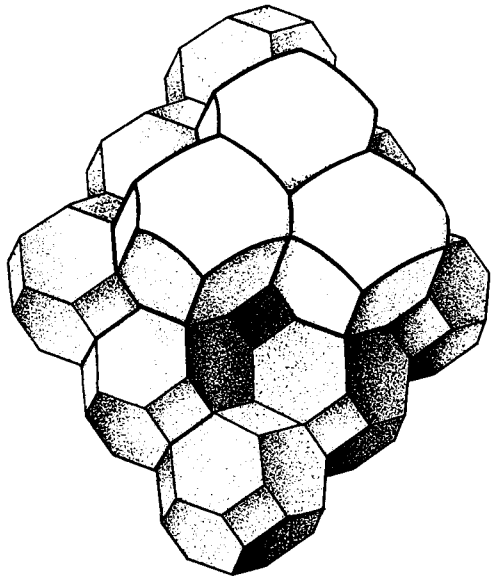

FIGURE 7. Three conventional epidermal polyhedra (4–4–3) resting upon a group of orthic 14-hedra (6–0–8), all of which are in prosenchymal orientation. The 14-hedra in this model, in parenchymal position, have been figured as typical of the cells in elder pith (Proc. Amer. Acad., 1923, 58, p. 554, Pl. I).

were described as "somewhat larger than those of the epidermis." The fact that the observations are consistent with a typical epidermis resting upon cells of twice their sectional area was not stated. Previously, after sampling a large number of living plants, Matzke had found epidermal and subepidermal cells "of approximately similar dimensions" in *Aloe aristata*. In the epidermis of its leaves he reported[5] that 200 cells had an average of 10.88 facets: 23 of them were of the pattern 4–4–3 (Fig. 6B), exceeded only by 34 of the 3–6–2 deviations (Fig. 6A). The foregoing observations all lead to the conclusion that the basic form of a simple epidermal cell is the 11-hedral bisection of a Kelvin 14-hedron.

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A typical shape of vegetable cells is needed to explain their contrasting orientation in parenchyma and prosenchyma, in which the hexagonal sections of the cells interdigitate laterally and vertically respectively. The layer of soap bubbles over the bottom of the jar tends to impose a prosenchymal arrangement on the overlying strata. The patterns in Figure 6 and the conventional orthic 14-hedra in Figure 7 illustrate that position, characteristic of cells which increase in number by vertical division, enlarging the girth of the stem. If, however, Figure 7 is rotated clockwise 35°, the 14-hedra present hexagonal facets above and below, as is characteristic of parenchyma. They then have 2 tiers of lateral facets, variations in which have been expressed in a series of diagrams very different from those in Figure 6 (cf. Amer. Journ. Botany, 1943, *30*, p. 80). They show why the 14-hedron of formula 0–12–2, occurring in bubbles, has not been found and is not likely to be found in parenchymal cells. These cells increase chiefly by transverse division, and parenchymal orientation is characteristic of pith cells in elongating stems. The Kelvin 14-hedron, turned about, accounts for the shape of parenchymal and prosenchymal cells in their 3 dimensions.

The Kelvin 14-hedron exists in 2 varieties. Five years before he became Lord Kelvin, Sir William Thompson wrote[40]—"Given a model of the plane-faced isotropic tetrakaidecahedron, it is easy to construct approximately a model of the *minimal tetrakaidecahedron*. . . . No shading could show satisfactorily the delicate curvature of the hexagonal faces." That shape, with undulating hexagonal facets and plane quadrilaterals with out-curved sides, has less surface area than any other uniform shape into which space may be divided, and in so far deserves Kelvin's designation of "minimal 14-hedron"; yet the plane-faced non-stackable 14-hedron of formula 0–12–2 has distinctly less surface. Later Kelvin referred to the minimal *plane-faced stackable* form, in which the 6 quadrilateral facets are squares, as the "*orthic 14-hedron*."

The determination of the curvature of the arcs in Kelvin's minimal 14-hedron, as he said, may be "easily carried to any degree of approximation that may be desired . . . though not worth the trouble." Accordingly its surface area has never been calculated. But, for the writer's benefit, Lifshitz[41] has shown that by substituting conical surfaces which resemble the Kelvin pattern, the reduction in surface area over that of an orthic 14-hedron of the same volume is "0.103 per cent." In a communication to the Nederlandsche Akademie Professor van Iterson[42] and, working under his direction, Meeuse in his doctor's thesis,[43] have shown that it is not the plane-faced orthic

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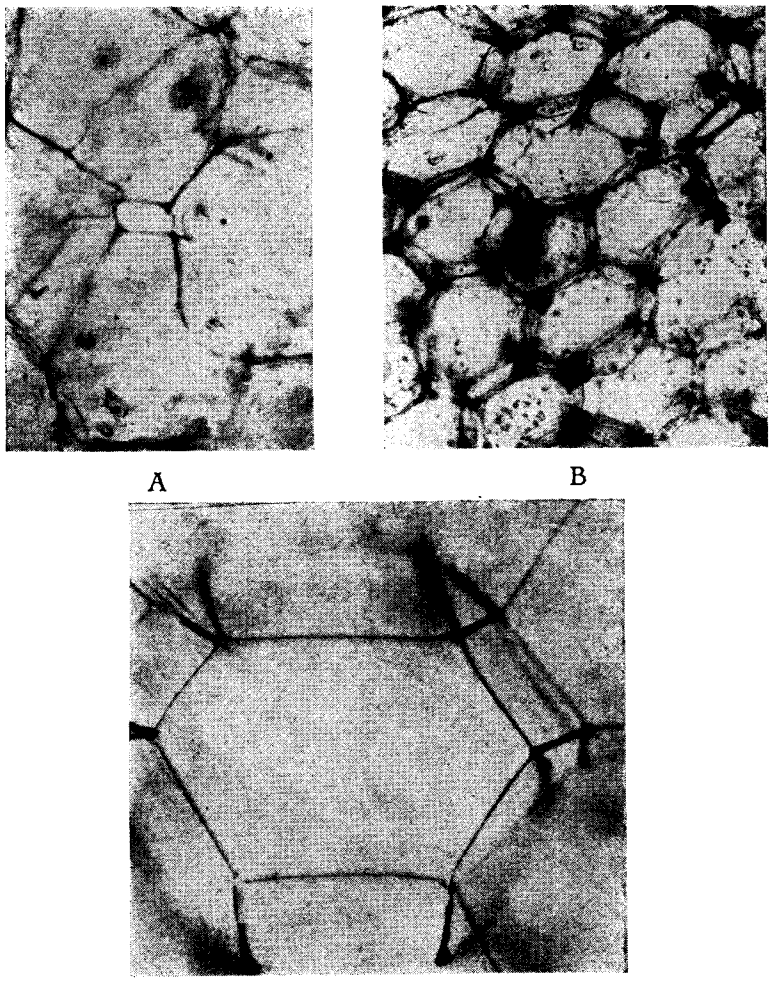

FIGURE 8. A. Quadrilateral facet suggesting the plane equilateral surfaces with slightly out-curved edges characteristic of Kelvin's minimal 14-hedron. Carrot, × 170. Fixed tissue, prepared and photographed by Prof. B. F. Lutman. B. Numerous quadrilateral facets of minimal form in the stem of a tomato plant. × 170. Photograph received from Prof. H. B. Reed, showing part of his Fig. 2, Amer. Jour. Bot., 33, 780, 1946. C. Facets of a parenchymal cell of *Asparagus sprengeri*, × 185. Prepared and photographed by Dr. A. D. J. Meeuse, included in Tab. III D of his Dissertation.[43]

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14-hedron of Kelvin which cells approach, but rather its geometrical refinement, the "body of Thomson" or Kelvin's *minimal 14-hedron*.

Van Iterson reported that for 15 years he had demonstrated that "numerous cells approach the orthic 14-hedron" in the cortical parenchyma of the root-tubers of *Asparagus sprengeri*—"an object in which it may be recognized almost at once even by an unpractised microscopist." He realized the significance of Meeuse's observation that all 4 sides of the quadrilateral facets commonly show a slight outward curvature. Meeuse admits that "it does not matter as a rule" whether we consider Kelvin's minimal or his orthic 14-hedron to be "the fundamental shape of cells: the latter is simpler in structure and easier to work with." In several photographs, however (one being our Fig. 8C) he has shown the subtler features of the minimal 14-hedron. Now that attention has been called to the slightly curved outlines of the quadrilateral facets, they are frequently observed. Figure 8A is from a section of a carrot prepared by Prof. B. F. Lutman for another purpose: in 8B several may be seen in the stem of a tomato plant studied by Prof. H. S. Reed.

"It is not to be expected that the 'ideal' cell shape will often be perfectly realized . . . a perfect likeness has never been reported before" (Meeuse). To find how frequently such shapes occur in Asparagus and Rhoeo—two tissues especially recommended by van Iterson and Meeuse for their regularity—Hulbary made a statistical study of 100 cells of each.[44] He found 73 different combinations of facets, with only 2 cells of the 6–0–8 formula, and concluded that "no pattern stands out as one from which all others may be derived."

This conclusion is reaffirmed by Prof. Hulbary in his full publication in the November number of the Amer. Jour. Bot. (35, 558–566, 1948), distributed after the completion of the present paper, yet allowing the insertion of this paragraph as a postscript. Having found that 100 parenchymal cells in *Rhoeo*, with an average of 14.24 facets, included 18 14-hedra, 2 of which were of the formula 6–0–8, Hulbary studied 100 14-hedra in that tissue. Eleven of them were 6–0–8, which accords with his previous percentage. For that and other reasons, the parenchyma of *Rhoeo* appears to be the most regular thus far statistically tabulated. However, Hulbary finds that 47 per cent of its 14-hedra have the configuration 4–4–6, and states that "the reason for the recurrence of this pattern is not apparent." A possible reason is that the 4–4–6 combination is a group of diverse patterns, including a hexagonal prism with 2 facets on every lateral face, arranged as figured and described in the Amer. Scientist, 34, 366, 1946; also such a prism with one undivided lateral face, one with 3 tiers of facets, and the rest with 2 tiers, as figured by Hulbary for *Rhoeo;* or a pentagonal prism with 3 tiers of facets on 2 lateral faces and 2 tiers on the other 3; etc.;

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whereas the meticulous 6–0–8 pattern, in a random elimination of the tetrahedral angles of a rhombic 12-hedron, would occur but once for 28 examples of the 4–4–6 (Reference 35). The irregular parenchyma of elder and *Eupatorium* sufficed for recognition of the typical 14-hedral shape, and whatever importance that type may have depends upon its application to all undifferentiated parenchyma. Hulbary, in *Ailanthus*, was the first to find the 6–0–8 combination in cells statistically studied (Amer. Jour. Bot., 31, 561–580, 1944); van Iterson and Meeuse have reported it in *Asparagus* with convincing photographs; Hulbary has now established statistically its occurrence in *Rhoeo*.

Bok,[45] in discussing bubbles without the benefit of Matzke's count that "more than five-sixths had 13, 14, or 15 contacts," argues that "froth chambers are approximations of regular dodecahedrons." Since at every corner in a foam each edge should meet 3 others at equal angles of approximately 109° 28′ 16″,[46] and in assembled *orthic* 14-hedra each edge meets 2 others at angles of 120° and the third at 90° (av. 110°), Bok rules out that shape as proposed through "a faulty trend of thought." He does not mention Kelvin's *minimal* 14-hedron, in which, through the curved edges observed by van Iterson and Meeuse, those angles approach the uniform angles of foam. With weaker surface tension and fewer pentagonal facets in cellular tissue, the approach to the Kelvin pattern is so manifest that that shape can confidently be accepted as a basis for many lines of further investigation. A reconstruction and volumetric study of the parenchymal cells in Eupatorium, arranged in their vertical columns, is sufficient ground for that expectation (Lewis[32]). The fundamental organization of the higher plants may then be indicated in a final diagram (Fig. 9).

Figure 9A is a vertical section of a column of 3 orthic 14-hedra surrounded peripherally by 26 portions of the same, 10 of which appear in the section. The simplest of these portions, as Dewar said of a similar arrangement of bubbles, are "pyramidal frustums, bounded externally by curved bubble films." The short shaft is encircled transversely by 2 layers of 9-hedra. It could be lengthened indefinitely by adding 14-hedra to the central column, with another layer of six 9-hedra for each addition. Over either end of the column there are 7 cells—an axial, apical cell surrounded by a circuit of 6 portions; and the total facets for all 7 are 50, whether the apical 14-hedron is sectioned through its lower, middle, or upper third, leaving it an 8-, 11- or 14-hedron respectively.

Figure 9B is a diagrammatic apical view of a larger shaft, in which 3 circuits of polyhedra surround the axial 8-hedral portion of an orthic 14-hedron. With modifications due to 2 schematic cell divi-

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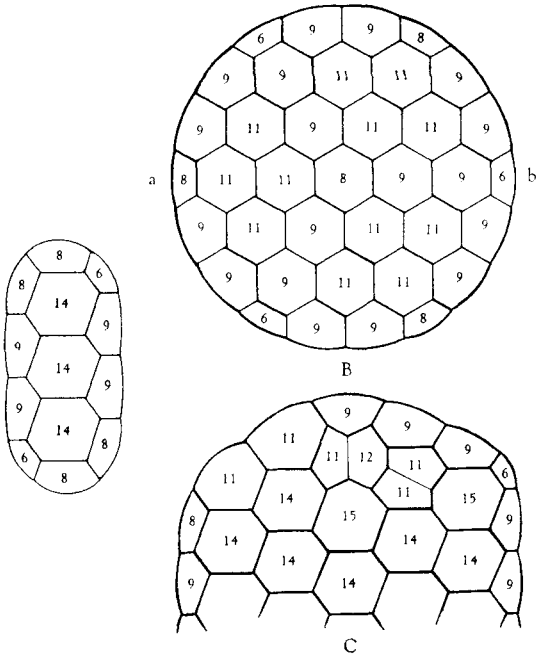

FIGURE 9. A. Median vertical section of a column of 3 orthic 14-hedra, enclosed in a layer of epidermal polyhedra which are portions of orthic 14-hedra. Numerals indicate the number of facets of each polyhedron. B and C. Two views of a similar but larger shaft, composed of 19 columns of parenchymal polyhedra, with the end of the entire shaft rounded to the extent shown in the median vertical section C. B is a diagrammatic surface view of the end of the shaft in C, with the number of facets of each polyhedron recorded. In C, 2 cell divisions have been introduced, converting the apical cell of B into the 9-hedron of C, and otherwise modifying the pattern.

sions, a vertical section of 9B, in the plane a to b, appears in 9C. At the apical surface in this simple scheme, it is seen that there is one sectioned 14-hedron at the summit of every vertical column. According to an old formula for finding the number of cells in honeycomb or kindred objects, when N is the number of circuits, the number of cells in a single transverse layer of the shaft (or in the surface view of the top, which is the same) is $3N(N+1)+1$. $6N$ is the number of epidermal cells in a cross section of the shaft, and $6(11N-2)$ is their number of facets: $3(N^2-N)+1$ is the number of parenchymal cells in such a cross section, and they all have 14 facets. These numbers,

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of course, may become averages, and the deduction of 12 facets in the epidermal layer may be transferred, in whole or in part, to the parenchyma.

Over the end of a shaft composed of 14-hedra, there is a further reduction of facets than occurs in the layers around the sides of the shaft. The numerals in Figure 9B indicate the number of facets of the polyhedra covering the rounded end of that shaft with 3 circuits, the sum of which is expressed in the general formula $33N^2 + 15N + 2$. The same number of facets (344) would occur in the flat end of a similar shaft cut out from an integrated mass of orthic 14-hedra, provided that the sharp cut edge at the junction of the horizontal and vertical sides of the cylinder was eliminated—it would not be there in bubbles or in liquid bodies (cf. Lewis,[32] p. 628).

The external mosaic covering the shaft and its ends consists entirely of hexagons except for the required loss of precisely 12 sides. In Figure 9B the loss is located in 3 cells which have quadrilateral facets externally; they would be matched by 3 others at the opposite end of the shaft. These 3 are 6-hedral cells (one at *b*). The peripheral 8-hedral cells in 9B (one at *a*) present hexagons externally, like the 8-hedral cells in Figure 9A.

In Figure 9C, the 2 hypothetical divisions which have been added are enough to suggest a meristem with dermatogen and plerome—a corpus and tunica. A vertical division of an axial orthic 14-hedron, in the midst of others like it, produces a pair of 11-hedra (formula 4–4–3), thereby introducing 20 pentagonal facets, 12 of which are formed on 4 adjacent cells. This may readily be visualized from the mutual relations of an entire and a bisected conventional model of either the orthic or minimal type. The 4–4–3 is a common facet combination, with 5 records in 50 small cells (Marvin[47]), one of them being, as in Figure 9C, half of a 14-hedron, vertically sectioned.[48] This division, in the figure, makes the underlying body a 15-hedron (5–3–6–1), matched by 3 cells in 150 (Hulbary), and it produces an epidermal 4–4–1, of which combination Matzke counted 11 in 200 epidermal cells of Aloe.

It is not to be supposed that cells occur as masses of 14-hedra to be disarranged by the subsequent introduction of division, as in a diagram, since the initial clusters arise by division, with its effects there from the outset. Nevertheless it appears that a typical geometric form for cells has been established, through Kelvin's mathematics, as a first step toward placing plant and animal cytology on an adequate geometrical basis. If his type forms are accepted as the source of

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scores of deviations—in part random deviations—the way is open for profitable consideration of many unsolved morphological problems.

Summary and Conclusion

An attempt has been made to present the simplest possible arrangement of undifferentiated cells and their intercellular spaces preliminary to studying the evolution of complex cell patterns. The shape of primitive cells in masses appears to depend on 5 paramount factors.

(1) *Geometric necessity.*—This is the bond whereby, in space-filling aggregations, bodies of equal size have been found to have an average of approximately 14 facets, whether they are cells, solids or bubbles. If a uniform shape is assumed they become regular 14-hedra. Geometrically it is impossible for them to be 15- or 13-hedra. Although the average of 14 is realized for bodies promiscuously assembled, special arrangements may reduce the facet number. Notably when equal spheres are stacked in cannon ball fashion before compression, they yield 12-hedra, each with 6 tetrahedral angles, at each of which 6 bodies should meet at a mathematical point. Failing to fulfill this exacting requirement leads toward the 14-hedral shape. Inherently a mass of 14-hedra must be enclosed in a surface layer, epidermal or epithelial, in which a single contact with the surrounding medium is substituted for contacts with 4 surrounding polyhedra. These 11-hedral peripheral cells have the form of bisected central 14-hedra. Yet a shaft formed of columns of 14-hedra cannot be covered by a layer of 11-hedra without a deduction of 12 facets in every transverse stratum. In accordance with Euler's law, the possible combinations of facets, corners and edges of any cell and of every mass of cells are geometrically determined.

(2) *Surface tension* and other forces resulting in minimal surface.—"This does not enter into the formation of compressed plastic spheres" (R. J. Piersol[49]). In liquid films tetrahedral angles are unstable, and their elimination leaves only the 14-hedron as the uniform space-filling possibility for bubbles and cells of least surface. With bubbles surface tension is sufficient to produce examples of all the unstackable combinations of 12, 14, 15 and 16 facets which, if isolated and regular, would have the least surface for their volume (Goldberg). Correlated with low surface tension, none of these shapes have as yet been found among cells. The downward deviation of the average number of facets of bubbles in unarranged foam to 13.70, as reported by Matzke, is unaccounted for; but his finding that the central bubbles, in a dish lined with those averaging 11 facets, show slightly higher average facets when their volume is 1/20 cc. than when their volume

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is 1/10 cc. (13.74 facets as compared with 13.69) is a trend which accords with the geometrical expectation. It appears improbable that irregular aggregates have less surface area than Kelvin's mathematical minimal pattern.

(3) *Cell division.*—This process, perhaps electro-chemical, is opposed to surface tension, since it increases the cellular surface. It need not change the average number of facets of the cell mass in which it occurs, but it introduces an abundance of pentagonal facets in any group of Kelvin 14-hedra, which otherwise could lack them altogether. Since divisions tend to be in a predominant plane, which would be transverse in stems increasing in length, and vertical in those increasing in girth, they cause the cells to be arranged in vertical parenchymal columns, or in transverse prosenchymal layers, respectively, as is essential for producing a mass of Kelvin 14-hedra.

(4) *Turgor.*—Also opposed to the contractile effect of surface forces is the expansion from turgor and growth whereby many cells cease to be isodiametric, and actively or passively become drawn out into elongate or stellate forms. Even though tall epidermal cells may become globular when isolated, they should not be regarded as spheres which by expansion have filled out their interstices, like peas in Buffon's experiment. Yet swollen peas often yield cell-like combinations of facets.

(5) *Organization.*—This is the elusive factor which Schleiden recognized as "paramount" more than a century ago, whereby growth and division are so controlled as to produce filaments, fibers, membranes or compact masses as may be proper for the organism. Fibers, as elongated 14-hedra, would be rendered short and inefficient by a few successive transverse divisions. In another century something more should be known regarding the nature of the "organizer," which coordinates the foregoing factors.

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LINEAR COMPRESSIONS TO 30,000 kg/cm², INCLUDING RELATIVELY INCOMPRESSIBLE SUBSTANCES

By P. W. Bridgman

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Introduction

This paper continues the program of measurement of linear compressions to 30,000 kg/cm^2, for which results for 16 comparatively compressible substances have already been published.[1] The particular object of these measurements is to obtain as accurately as possible the deviations of the compression from linearity with pressure. The substances measured formerly were relatively compressible; it was desired to now extend the measurements to less compressible substances. Formerly, measurements of sufficient accuracy for the purpose in hand did not put too stringent demands on the apparatus. Some 25 unsuccessful attempts showed, however, that the former apparatus was not adequate for many of the more incompressible substances, so that the first task in extending the measurements to such substances has been to refine the apparatus.

The refinement of the apparatus proved to be a more serious undertaking than had been anticipated, and much time was spent in the preliminary work. Furthermore, more time was spent in the work of development than would otherwise have been necessary because of my preconception about the nature of the physical situation. This preconception was that the relation between linear dimensions and pressure for ordinary substances would be smooth and single valued, so that the smoothness of the results could be used as a criterion of the satisfactory functioning of the apparatus. After exhaustive checking, the conclusion seemed to be forced that for many substances the relation is not smooth, but there are small-scale irregularities characteristic of the particular substance, which can never be made to vanish. On reflection it is perhaps not unnatural that this should be the situation, when the magnitude of the pressures and the practical impossibility of obtaining any actual substance in a truly homogeneous condition are considered. That this is the case, however, makes much more difficult the task of obtaining truly significant values for

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the second and higher order terms in the compression of the incompressible materials, and places the theoretical physicist who must use the experimental results under a corresponding embarrassment. The difficulty is greatest for the relatively hard materials of this paper, which are at the same time relatively incompressible. There is comparatively little uncertainty in the deviations from linearity of the softer materials, since for these materials the irregularities are small compared with the deviations from linearity.

The materials measured in the following are in many cases the identical specimens which have previously been measured over a narrower pressure range, usually up to 12,000 kg/cm². A number of the elements, however, are of more recent origin. With the completion of this paper nearly all the specimens of inorganic materials which were formerly measured in the range to 12,000 kg/cm² have now been measured in the range to 30,000. A few of the former specimens were unavailable because of accidents of one sort or another.

In the following the more compressible specimens were measured with the lever piezometer of the former paper, the new more sensitive piezometer not being adaptable for them. The dividing line is approximately at aluminum, all substances more compressible than this being measured with the former piezometer. The materials may be classified as elements (pure metals), alloys and intermetallic compounds, and minerals, many of them in the form of single crystals, and a few organic single crystals.

The Apparatus and Method

The new apparatus is the "lever piezometer" of my former work,[2] improved in two essential respects. In this apparatus the specimen rests against the short arm of a lever, the angular position of which alters when the relative dimensions of the specimen and the housing of the lever change under the differential compression brought about by the application of hydrostatic pressure to the fluid medium in which all parts of the apparatus are immersed. The motion of the long arm of the lever is measured in terms of the alteration of resistance of a wire attached to it and sliding over a cross wire attached to the housing. It is evident that the lever itself must be positive in its action, without backlash or other indefiniteness, and that the surface of the measuring wire and the cross wire must be smooth. The improvements consist in the use of a more uniform slide wire and in a better method of pivoting the lever.

With regard to the wire, a simple consideration will indicate the degree of perfection required in the surface. The electrical parameters of the potentiometer circuit with which the resistance of the

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slide wire was measured were such that a relative shortening of 2×10^{-6} cm of specimen with respect to the housing could be detected. This corresponds to the effect of 10 kg/cm^2 on platinum. Since the magnifying power of the lever was about 10, this demands that there be no scratches or other surface imperfections as much as 2×10^{-5} cm wide on the wire. Otherwise the readings will jump spasmodically when the scratch moves across the cross-wire. This of course presupposes that the material of the wire underneath its surface is uniform to a corresponding degree. In the former work the wire had been made of nichrome. This had been obtained from the manufacturer, The Driver Harris Company. Its diameter as purchased was 0.016 inch, and it was drawn down further to 0.013 inch in several stages through special diamond dies. The wire so drawn was examined microscopically and calibrated electrically for uniformity, and the best portions used in the piezometer. This was sufficiently good for the former measurements. However, the surface of this wire disclosed blemishes under the microscope which could never be got rid of. In the attempt to eliminate them for the present work, the wire was subjected to various processes of preliminary polishing or grinding, some of them rather elaborate, before the final drawing, but without success. Finally, half a dozen different sorts of high resistance wire made by Driver Harris were examined to find if any were superior to nichrome. I am indebted to the manufacturers for selecting coils which were especially smooth. These wires were then further drawn in the machine shop of the laboratory from 0.014 to 0.013 inches in a new diamond die specially made and polished for this work. This drawing was done in the lathe, by attaching the wire to the screw cutting feed, a device which I owe to the suggestion of my mechanic, Mr. Charles Chase. Drawing by hand is too jumpy and irregular. The wires so made were mounted in the calibrating device and their uniformity studied. Of the various alloys tried, "Iconel" or "Nirex" proved the best and much superior to Nichrome. This alloy is composed of 13% Cr, 8% Fe, balance Ni. The various constants of this material, specific resistance and compressibility, were determined and found to be not far from those of nichrome, so that only minor changes were required in the various correction terms. Its temperature coefficient of resistance is also so small as to introduce no error under the conditions of use.

The second major improvement concerns the pivoting of the lever. Formerly the lever rocked on two hardened steel points, pressed by a spring into a crater and notch. The points, of course, were really portions of spheres with finite radius and the bearing against crater or notch was on two tangents. The point of leverage was therefore

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indefinite by a possible maximum of the distance of separation between the tangents. At the two points of contact angular motion necessarily involved surface slip and friction with resultant lack of perfect definiteness and reproducibility. The improvement consisted of replacing the steel points with a flat steel spring clamped between hardened clamps, as shown in Figure 1. Not only does the flat steel spring replace the former pivoting points, but it also eliminates the necessity for the spring by which the points were formerly maintained in contact with their seats. This improvement in design permits such an alteration of proportions that the multiplying power of the lever could be increased from approximately 5 to approximately 10. The flat spring in the final form was 0.007 inches thick; this thickness was arrived at by trial. The force exerted by this spring necessarily varies with the displacement of the lever. By measurement it was found that the maximum variation in the force at the end of the long arm, corresponding to the most compressible of any of the substances in the following, was from 2 to 6 ounces. Taking account of the multiplication and cross section of the specimen, this corresponds to a maximum change of 30 kg/cm^2 in the one-sided compressional force exerted on the specimen by the method of mounting; this is negligible compared with the maximum pressure of 30,000.

The contact between the specimen and the short arm of the lever was still by a hardened steel "point" resting in a hardened crater. To make this contact as definite as possible the "point" was made in the form of the three-quarter portion of a sphere of radius .005 inch, made with a special tool and shown in Figure 2, highly polished.

The full dimensions of the specimen taken by the piezometer were 0.75 inches in length and 0.20 inches in diameter. For some specimens the diameter was reduced to 0.18. In some cases, particularly with single crystals of minerals, the full length was not available. In these cases a shorter specimen was used extended by a piece of American ingot iron, the compression of which is known.

The lever piezometer thus constructed was calibrated much as before. The short arm was moved a known distance with a Brown and Sharpe high-precision micrometer screw, cut on a specially large barrel and provided with a head graduated to 0.0001 inch and reading by estimation to 0.00001 inch. The multiplying power was determined by measuring simultaneously the motion of the long arm with a suitably mounted microscope, and the changes in potentiometer setting due to the motion of the slide wire. The piezometer was mounted in a temperature bath for this purpose. These measurements established the sufficient uniformity of the slide wire and the

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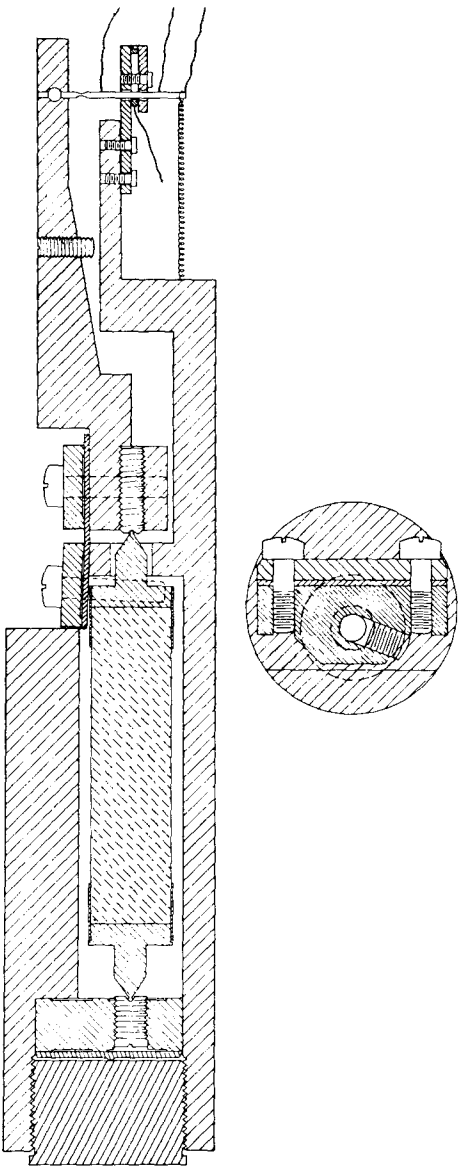

FIGURE 1. The modified lever piezometer, with spring replacing pivots.

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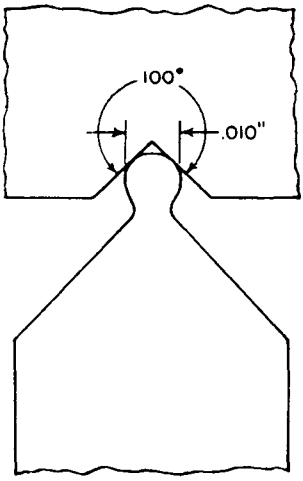

FIGURE 2. The ball contact for the specimen.

linearity of the relation between motion of short arm and the slide wire.

The calculations and corrections were essentially as before and need not be described further. Special measurements had to be made of the effect of pressure on resistance of Nirex and also of its compressibility. The latter will be described presently. The pressure coefficient of resistance, terminals attached to the wire, was -2.82×10^{-7}, pressure in kg/cm^2 units.

Even after the major improvements had been effected, the piezometer did not at once function satisfactorily and some 20 preliminary runs were made incorporating various minor refinements. The most important of these was a three-point contact between the mounting and the block supporting the lower end of the specimen. This block contained a screw adjustment by which the absolute position of the specimen could be altered so as to bring into operation one or another part of the slide wire. It was established that there was no dependence of the pressure effects on the absolute setting on the wire. It was also necessary to so design the apparatus as to avoid all regions where liquid might be entrapped, as between the rounded end of the pivot and its seat; otherwise irregular effects were produced by non-hydrostatic components of stress.

It has already been stated that irregularities persisted after all improvements; the outstanding irregularities were finally ascribed to the specimens themselves rather than the apparatus. A detailed

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presentation of all the evidence on which this conviction rests would take too much space to be feasible. In brief, the argument rests on the discovery of patterns characteristic of the individual materials which persist through variations in the treatment given the specimen. Often these patterns were irregular, but the argument was much strengthened by the existence of substances with smooth patterns. Of special and decisive significance was the behavior of four different specimens of martensite with progressively different heat treatments. These all exhibited hysteresis loops, the readings not being single valued with pressure but lying on different curves for increasing and decreasing pressure. The individual points lie smoothly, within limits of 2 and 3 times the maximum sensitiveness of the potentiometer, on one or other branch of the hysteresis loop, and there is a consistent variation in the width of the loop with the heat treatment.

It was a matter of extraordinary good fortune that soft iron itself is one of the substances which not only does not exhibit hysteresis but also for which the results are smooth. This smoothness is characteristic of several grades of iron investigated, namely American ingot iron, for which the fiducial absolute determination of compressibility has already been made,[3] a single crystal of pure iron, and a pure carbonyl iron. The results for these three grades of iron were very close to each other. Since the piezometer itself is made of iron and since the measurements with the lever piezometer are all differential, it is obvious that irregularity in the iron itself would have seriously limited any information to be obtained.

In addition to the characteristic patterns of minor deviation from linearity, irregular or smooth, a number of substances showed an entirely different sort of thing, namely cusps or breaks in the direction of the tangent (transitions of the second kind) which have been found before for other more compressible substances[4] and which are doubtless of more fundamental physical significance.

The results now follow. In most cases the irregularities are so small that the mean results are given, smoothing over the irregularities, but with a statement of the nature of the irregularities including any consistent dependence on previous treatment of the specimen. Some quantitative indication is attempted of the magnitude of the irregularities by giving the average deviation of a single reading from a smooth curve. This is given in percentage of the total shortening of the specimen under the maximum pressure instead of as percentage of the differential shortening, as has been the practice in some previous papers. The present practice is obviously better adapted to the materials of this paper, which include substances with nearly the same compressibility as iron and therefore with a differential shortening

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which on occasion may become vanishingly small. In general, a run consisted of 18 readings at regular pressure intervals with increasing and decreasing pressure, the decreasing readings being staggered between the increasing readings. Before the run the sample was seasoned by several applications and release of pressure. The seasoning routine was in almost all cases the same. Unless it is specially mentioned it is to be understood that the preliminary seasoning was by three applications of 30,000 kg/cm² at room temperature.

The arrangement is: elements, alloys and intermetallic compounds, minerals, and organic crystals. Within each group the arrangement is by increasing compression under the maximum pressure. All measurements were made at room temperature, which varied from 23° to 26°. In the measurements and calculations, one more significant figure was used than is retained in the tables. The results are reproduced by tabulating volume decrements, or decrements of length, at intervals of 5,000 kg/cm². In view of the diversity of the results this seemed better than attempting to reproduce them by an analytical formula, although in many cases a second degree expression would have sufficed. In some cases, when the hysteresis pattern was especially prominent, the results with increasing and decreasing pressure separately are reproduced. The volume decrements listed in the tables were calculated from the measured changes of length, retaining second-order terms. That is, for an isotropic substance,

$$|\Delta V/V_0| = 3\,|\Delta l/l_0|\,\{\,1 - |\Delta l/l_0|\,\}\,,$$

with corresponding expressions for non-cubic crystals.

The Results

Elements

Iridium. This material I owe to the courtesy of Baker and Company, who fabricated it especially and loaned it to me for the measurements. The original slug was "worked from a sintered powder-metallurgy bar." Baker and Company described the density of a bar so formed as "practically 100%." It was 0.180 inches in diameter and 0.75 inches long; it was ground from the sintered slug. After receiving it the ends were trued flat and parallel by lapping. The results are given in Table I. The average deviation of a single reading from a smooth curve was 0.6 per cent of the shortening at the maximum. The irregularities showed no consistent pattern; in particular there was no appreciable hysteresis. It will be noticed that within the limits of error the relation between pressure and volume decrement is linear. The relation between change of length and pressure was, however, distinctly not linear, with curvature in

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TABLE I

COMPRESSION OF ELEMENTS

Pressure kg/cm²	Iridium	Tungsten $\Delta V/V_0$		Ruthenium	Platinum	Molybdenum	Rhodium	Tantalum $\Delta V/V_0$		Cobalt, single crystal		
	$\Delta V/V_0$	Single Crystal	Drawn Rod	$\Delta V/V_0$	$\Delta V/V_0$	$\Delta V/V_0$	$\Delta V/V_0$	99.9%	99.95+%	$(\Delta l/l_0)_{\parallel}$	$(\Delta l/l_0)\perp$	$\Delta V/V_0$
5,000	.00137	.00155	.00152	.00154	.00176	.00179	.00180	.00244	.00243	.00087	.00083	.00253
10,000	.00272	.00309	.00301	.00312	.00351	.00357	.00361	.00488	.00485	.00172	.00166	.00504
15,000	.00408	.00475	.00458	.00477	.00526	.00536	.00540	.00728	.00726	.00260	.00251	.00760
20,000	.00545	.00634	.00612	.00645	.00701	.00714	.00719	.00969	.00967	.00347	.00331	.01006
25,000	.00683	.00797	.00765	.00818	.00877	.00891	.00896	.01208	.01208	.00434	.00412	.01253
30,000	.00818	.00959	.00917	.00989	.01048	.01064	.01071	.01447	.01448	.00520	.00490	.01492
Percentage Deviation from Smooth Curve	0.61	0.85	0.60	0.80	0.69	0.61	0.65	0.12	0.16	0.13	0.30	

Pressure kg/cm²	Nickel	Palladium	Gold	Columbium $\Delta V/V_0$		Iron $\Delta V/V_0$			Copper	Titanium
	$\Delta V/V_0$	$\Delta V/V_0$	$\Delta V/V_0$	Increasing	Decreasing	American Ingot	Single Crystal	Carbonyl	$\Delta V/V_0$	$\Delta V/V_0$
5,000	.00277	.00267	.00281	.00289	.00276	.00289	.00289	.00288	.00353	.00449
10,000	.00479*	.00517	.00558	.00569	.00556	.00575	.00575	.00572	.00696	.00900
15,000	.00750*	.00761†	.00831	.00842	.00836	.00856	.00856	.00853	.01039	.01332
20,000	.01001	.01015†	.01101	.01115	.01113	.01133	.01133	.01130	.01370	.01810
25,000	.01262	.01273	.01367	.01386	.01385	.01407	.01407	.01402	.01695	.02174
30,000	.01515	.01522	.01626	.01649		.01676	.01676	.01667	.02010	.02581
Percentage Deviation from Smooth Curve	0.12	0.18	0.03	0.014		0.012	0.012	0.015	0.14	0.58

*Cusp at 10,500 †Cusp at 16,500

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TABLE I (Continued)
COMPRESSION OF ELEMENTS

Pressure kg/cm²	Silver	Silicon	Beryllium	Germanium	Aluminum	Antimony Single Crystal			
	$\Delta V/V_0$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$\Delta V/V_0$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)_{8°}$	$(\Delta l/l_0)_{\parallel}$ Calc.	$\Delta V/V_0$
5,000	.00473	.00491	.00158	.00623	.00668	.00232	.00770	.00789	.01248
10,000	.00938	.00965	.00309	.01237	.01312	.00466	.01402	.01498	.02414
15,000	.01385	.01433	.00460	.01826	.01932	.00688	.02008	.02144	.03486
20,000	.61820	.01888	.00604	.02394	.02520	.00897	.02550	.02722	.04459
25,000	.02236	.02332	.00745	.02950	.03090	.01103	.03055	.03262	.05384
30,000	.02619	.02755	.00878	.03488	.03642	.01299	.03522	.03760	.06243
Percentage Deviation from Smooth Curve	0.27	0.18	0.41	0.28	0.26	0.40	0.48		

Pressure kg/cm²	Zinc Single Crystal			Thorium	Tin Single Crystal			Tellurium Single Crystal		
	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)$	$\Delta V/V_0$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)$	$\Delta V/V_0$	$(\Delta l/l_0)\perp$	$(\Delta l/l_0)_{\parallel}$	$\Delta V/V_0$
5,000	.00076	.00644	.00794	.00933	.00289	.00314	.00889	.01113	−.00222	.02011
10,000	.00151	.01277	.01575	.01733	.00561	.00621	.01732	.02138	−.00390	.03915
15,000	.00227	.01849	.02293	.02472	.00819	.00915	.02530	.03002	−.00512	.05551
20,000	.00303	.02376	.02967	.03188	.01065	.01192	.03283	.03726	−.00603	.06943
25,000	.00381	.02879	.03618	.03882	.01304	.01455	.04004	.04384	−.00667	.08234
30,000	.00459	.03356	.04242	.04555	.01534	.01704	.04691	.04946	−.00720	.09346
Percentage Deviation from Smooth Curve	0.50	0.54		0.45	0.37	0.38		0.57	0.52	

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the "abnormal" direction, that is, a linear compression increasing more rapidly than linearly with pressure. The compression of Ir has been formerly measured[5] to 12,000. The former compression at 10,000 at 25°, using the 1940 compression of iron,[6] was .00268 against .00272 found now.

Tungsten. Measurements were made on two specimens. One was drawn rod obtained in 1939 from the Fansteel Metallurgical Corporation and described by them as of 99.9 +%, R_2O_3 .002% maximum, purity. This had been used in several of the preliminary measurements and had been exposed to four applications of the maximum pressure before the measurements recorded here. The other specimen was a single crystal, which I obtained through the courtesy of Dr. Irving Langmuir some 25 years ago. It was made by the German General Electric Company by prolonged resistance-heating the sintered rod in vacuum until it recrystallized into a single crystal, as indicated by the reflection pattern from the surface. The original diameter was about 0.25 inch. During the recrystallization process it had sagged a little from its own weight between the electrodes on which it rested. The specimen used above was ground out of this crystal so as to be straight. This is the same crystal on which I have previously made measurements, in particular of the elastic constants.[7] This single crystal was measured once to the maximum before the measurements recorded in Table I. The table indicates a greater experimental irregularity for the single crystal than for the drawn rod. The compression of the latter is distinctly less than for the crystal, and is sensibly linear in pressure. The single crystal, on the other hand, deviates from linearity in the abnormal direction. This is doubtless connected with its larger compressibility, and indicates the presence of internal inhomogeneities, which is not surprising in view of the method of formation. The irregularities for the drawn rod followed no definite pattern. For the crystal, on the other hand, there was definite hysteresis, and the width of the hysteresis loop was about twice as great on the first application of pressure as on the second. Furthermore, the hysteresis was in the abnormal direction, the shortening being in advance of the pressure instead of lagging behind it. The maximum width of the hysteresis loop on the second application of pressure was about 2.3 per cent of the maximum distortion. The value previously obtained[7] for the compression at 10,000 for the identical crystal corrected for the 1940 value of iron was .00317 against .00309 above. The corrected former results also indicated a second degree term of abnormal sign.

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Ruthenium. This was a swaged rod, obtained some 25 years ago from Johnson and Mathey of London, and already measured[8] to 12,000 kg/cm^2. "It was not perfectly regular in appearance, but appeared as if there might be seams in it." The irregularities in the pressure effects were unusually large. There is a hysteresis loop of abnormal sense of maximum width equivalent to nearly 6 per cent of the maximum distortion. There were large initial irregularities; the initial points were discarded in the calculation of the average deviations. The relation between volume compression and pressure fails to be linear by an unusually large amount in the abnormal direction. Previous measurements on the identical specimen to 12,000 yielded for the corrected compression at 10,000 .00333 against .00312. Altogether, the indication is of an abnormally high state of internal strain brought about by the increased pressure range.

Platinum. This was a recent specimen, obtained on loan from Baker and Company. It was worked from a casting. The preliminary treatment was the same as for iridium, already described. The deviation pattern indicates a definite hysteresis of the normal sign, the maximum width of the loop being 1.2 per cent of the maximum distortion. The compression deviates slightly from linearity with pressure in the normal direction. The former value[9] of the compression at 10,000 corrected for the 1940 iron and measured on another sample over the range to 12,000, was .00355 against .00351 found now.

Molybdenum. This was rod, obtained in 1939 from the Fansteel Metallurgical Corporation and described by them as of purity 99.9 + %, Fe 0.005% Maximum, C none. It had been subjected to several preliminary applications of pressure in measurements during the development of the apparatus. The pattern of deviation indicates a normal hysteresis loop of width 1.2 per cent of the maximum distortion. The deviation of the compression from linearity with pressure is definite and in the normal direction. The former compression[10] at 10,000 corrected for the 1940 iron, and measured on another specimen over the range to 12,000 was .00361, against .00357 above.

Rhodium. This was obtained on loan from Baker and Company at the same time as the iridium and platinum. It was annealed and had been formed by casting and worked to dimensions by grinding. The preliminary treatment was the same as for the other two. The pattern of deviation from linearity indicates a very small hysteresis in the normal direction of the order of one per cent of the maximum distortion, but the loop is pretty well obscured by the other irregu-

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larities. The deviation from linearity is in the normal direction. The former compression[11] at 10,000 corrected to the 1940 value of iron, on a specimen obtained from Johnson Mathey measured over the range to 12,000, was .00345 against .00361.

Tantalum. Measurements were made on two specimens, the first obtained from the Fansteel Company in 1939 and said to be of 99.9% purity, Fe 0.01% Maximum, C 0.003% Maximum, and the second obtained from the same source in 1946 and said to be of slightly greater purity, 99.95%. Both had been annealed by the Company. This material was rather extensively investigated in the preliminary measurements, the pattern of irregularity being pronounced and characteristic. The first specimen was subjected to six applications of 30,000 and the second to two applications before the final measurements. Through all these applications there was a persistent hysteresis in the normal direction. The width of the loop on the final application was 1.04 per cent of the maximum distortion for the first specimen and 0.97 per cent for the second. The loop is so definite that the deviations of a single point from the smooth curve given in Table I are deviations from the two branches of the loop, instead of deviations from the mean curve drawn through the center of the loop, as has been the case for the previous metals. The compressions listed in Table I are, however, the compressions corresponding to the mid-curve of the loop. It will be noticed that the deviation from linearity, that is, the second order term in the compression, is less for the purer of the two specimens. This specimen had not been so well seasoned as the other, however, and its hysteresis loop was definitely not completely closed at the lower end. It is probable that the second order term of the less pure sample should be given greater significance. The former compression[12] at 10,000 corrected for the 1940 Fe, measured on a specimen obtained from Fansteel before 1923 in the range to 12,000, was .00488 against .00488 and .00485 found now. The second-order term of the former specimen had the abnormal sign.

Cobalt. This crystallizes in the hexagonal system, so that measurements in two orientations are necessary for complete characterization. I was fortunate to obtain from Dr. Bozorth of the Bell Telephone Laboratories single-crystal specimens in the two orientations, parallel and perpendicular to the hexagonal axis. The original source of the material was the Katanga Company. The analysis of this particular lot was not taken, but a comparable batch gave Fe 0.05% and Cu 0.01%. It was heat treated in pure hydrogen just below the melting point. Both of these specimens were unusually smooth, without

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definite hysteresis. This is by far the most satisfactory material of any described to this point. The deviation of the volume compression from linearity is definite and in the normal direction. The linear compressions in the two directions are approximately the same, which would be expected since the crystal is a close packed structure of *spheres*. The former[13] volume compression at 10,000 corrected for the 1940 iron, and measured in the range to 12,000 on a polycrystalline aggregate, was .00528 against .00504 now.

Nickel. This material in single-crystal form, I also owe to the courtesy of Dr. Bozorth. Since it is cubic, measurements in a single direction suffice. The original source of the material was the International Nickel Company. The analysis was not stated, but the purity is thought to be comparable to that of a single crystal of iron, also from Dr. Bozorth, the analysis of which will be stated later. Like cobalt it had been heat treated in hydrogen near the melting point. A considerable number of measurements were made on this specimen since it was evident from the first that there was something peculiar about it. It was first pressure seasoned by two applications of 30,000. Four sets of measurements to 30,000 were then made in the former inadequately sensitive apparatus, then a measurement in the final apparatus. No consistency was obtained. The nickel was then annealed by heating to a red heat in an evacuated tube for one hour and cooled with the furnace. Two measurements to 30,000 were then made with the final apparatus, then three seasoning applications were made of 30,000 without measurement, and then the final measurement to 30,000. All the measurements with the final apparatus indicated the same thing, a break in direction, or a transition of the second kind. The parameters of this second order transition changed with successive applications of pressure, the pressure at which the discontinuity occurred fluctuating between 10,000 and 20,000 kg/cm², and the amount of discontinuity also fluctuating. On the final measurements the magnitude of the discontinuity reached its largest value. The experimental points of the last run are shown in Figure 3. These correspond to the values given in Table I. The break at 10,600 amounts to a discontinuity in $1/v_0\left(\frac{\partial v}{\partial p}\right)_\tau$ of 6.9×10^{-8} (kg/cm² units) in the direction of an *increased* compressibility at higher pressure. The effect of pressure on the electrical resistance of nickel should obviously be studied in the same range. Previous measurements[14] have been made in the range to 12,000 on two polycrystalline specimens of presumably inferior purity. The corrected compressions at 10,000 were .00518 and .00514 against .00479 above. The differ-

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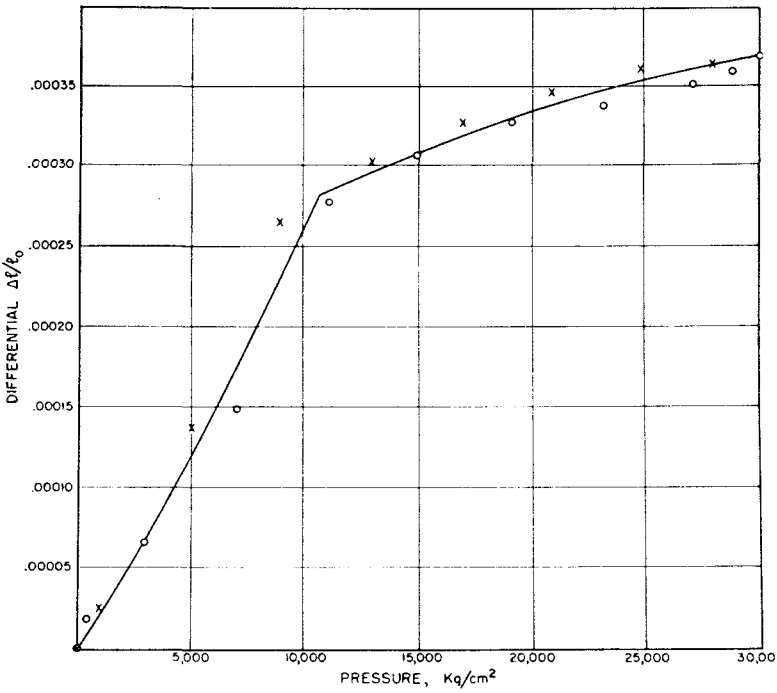

FIGURE 3. The experimental values for the differential change of length of nickel. The circles are for increasing pressure and the crosses for decreasing.

ence is extreme and doubtless connected with the second-order transition; it has been my experience that such a transition may be suppressed if the specimen is subject to constraint.

Palladium. This was obtained on loan from Baker and Company in the same batch as the iridium, rhodium, and platinum already described. It was worked from a casting and drawn to diameter. The individual points lie rather smoothly, without probable hysteresis. There is a definite cusp, or transition of the second kind, at 16,500 kg/cm², where the volume compressibility, $1/v_0\left(\frac{\partial v}{\partial p}\right)_\tau$, has a discontinuity of 6.9×10^{-8}, the compressibility being *greater* at higher pressures. The amount of the discontinuity is by chance the same as for nickel and in the same direction. The electrical resistance of palladium has not yet been measured in this pressure range. The previous[15] corrected compression at 10,000 of a specimen in wire form measured

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over the 12,000 range was .00507, exactly the same as the present value.

Gold. This was "highest purity" material obtained a number of years ago from Baker and Company. Gold from the same stock has been used in many of my calibrations of piezometers to 50,000 and 100,000. It was formed for the present measurements by cold extrusion from 0.25 inch diameter to 0.20 inch, annealed at red heat, pressure-seasoned twice to 30,000, and measured once in the preliminary piezometer to 30,000 and again in the final piezometer. The points lay smoothly but with a consistent hysteresis not expected for this soft material. It was reannealed at a red heat, pressure-seasoned by three applications of 30,000, and again measured in the final piezometer. The previous pattern repeated, the hysteresis being in the abnormal direction, and in amount nearly the same as before. The width of the hysteresis loop was equal to 0.48 per cent of the maximum distortion. The mean deviation from the smooth curve given in the table is the deviation from the branches of the loop, not from the mean curve through the center of the loop. It will be noticed that the individual points lie with unusual smoothness; the hysteresis for this specimen is undoubtedly real. The deviation of volume compression from linearity in pressure is in the normal direction. The previous[16] corrected compression at 10,000 for the 12,000 range was .00556 against .00558 now.

Columbium. This was obtained from the Fansteel Company in 1946, described simply as "special high purity material." It had been annealed by them. It was pressure seasoned to 30,000 twice, then measured once in the preliminary piezometer and again in the final piezometer to 30,000. The pattern of hysteresis was so distinctive that it was annealed again by heating to 900° C. in vacuum, pressure-seasoned three times to 30,000 and again measured in the final piezometer. The pattern was again much the same as before, with a hysteresis loop not of the conventional shape, but the major part of the loop was below 15,000 kg/cm^2, and above that the loop dragged out in a rapidly narrowing tail. The narrowing at the high pressure end was somewhat more pronounced after the second annealing and seasoning. The hysteresis pattern is so definite and characteristic that the results for both increasing and decreasing pressure are reproduced in the table. It will be noticed that the hysteresis is in the abnormal direction. The deviation from linearity is in the normal direction. The smoothness of the individual points, which is calculated from the individual branches of the loop, is quite exceptional, by far the best recorded up to this point. The previous[17]

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corrected compression at 10,000 for the 12,000 range measured on a specimen obtained from Fansteel in approximately 1929, was .00559, which is between the two values .00569 and .00556 now found for the two branches of the loop.

Iron. Measurements were made on three different specimens. The first was American Ingot iron from the same bar as that used in all my calibrations and for which the absolute compression has been previously determined by another method.[3] The particular specimen used here had been subjected to two measurements to 30,000 kg/cm^2 before the final measurements recorded in the table. These recorded values are identical with the values of the absolute compression already given, the various small corrections to the piezometer being determined from these measurements so as to give identity. The second specimen was a single crystal which I owe to the courtesy of Dr. R. M. Bozorth. It is from the same batch as that for which other constants have been published by Dr. Bozorth[18] and had the analysis: Ni 0.008%, Si 0.002%, C 0.008%, S 0.001%, Co, Cr, Mo, Mn, O less than 0.001%, Cu less than 0.005%. It was subjected to two preliminary applications of 30,000 before the final measurements. The compression measurements on this single crystal gave results completely indistinguishable from those with the American Ingot iron, so that it is not tabulated separately. The third specimen was a "hydrogen purified carbonyl" iron which I owe to the courtesy of Dr. R. F. Mehl of the Pittsburgh Institute of Technology. It had been heat-treated in hydrogen for 500 hours at 1200° C. A typical analysis, not on the identical specimen, was Cu and Mn about 0.01%, with spectroscopic traces of Si, Mn, Sn, Ni and Al. The preliminary seasoning of this was not as elaborate as for the other two specimens, consisting only of a single application of 10,000 kg/cm^2. The compression under 30,000 is about 0.5 per cent less than for the two other specimens. None of these three specimens showed the slightest indication of hysteresis. The exceptional smoothness of the results is to be noted. It has already been commented on how fortunate it is that the material of which the piezometer is constructed is one which shows no irregularities under pressure. The deviation from linearity is in the normal direction and about the same in magnitude as that of gold.

Copper. This was electrolytic copper of 99.999 per cent purity, which I owe to the courtesy of Dr. A. B. Greniger a number of years ago, at that time a member of the Harvard Department of Metallurgy. It was subjected to six series of measurements to 30,000, being used in the preliminary improvement of the apparatus. Only the last

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measurement was with the apparatus in the final form, but with the next to the last the final form was so nearly attained that nearly full significance can be attached to the results. This specimen of copper never settled down to smooth single-valued variation with pressure, but a definite hysteresis in the normal direction persisted, the width of the loop being very nearly the same on the last two runs. The loop was not completely closed at the low pressure end. In the table the mean points are shown, for the mid-curve of the loop, but the deviations from smoothness of the single readings (0.14%) are deviations from the branches of the loop. The width of the loop was 1.4 per cent of the maximum distortion. The deviation from linearity is in the normal direction. The former[19] corrected compression at 10,000 for less pure Cu in the 12,000 range was .00700 against .00696 now.

Titanium. This was a piece of the recently produced "ductile" titanium, which I owe to the courtesy of the Remington Arms Company. It presumably is of materially higher purity than the specimen formerly measured in 1929.[19a] The specimen was turned to dimensions from a rod 0.25 inch in diameter, presumably a drawn rod. Titanium is known to crystallize in the hexagonal system, so that a full characterization of the compression properties would demand two orientations from a single crystal. The axial ratio for this substance is given by Wyckoff as 1.60, which is so close to that for the hexagonal close packed arrangement of spheres, 1.63, that it is probable that the compressibility is nearly equal in the crystallographically different directions. The irregularity of the results for this material was somewhat greater than usual and great enough to obscure any hysteresis. An adequate explanation is failure of the compressibility to be completely isotropic because of the hexagonal crystal system. The former compression at 10,000 was .00808 against .00900 found now. The unusually large difference is doubtless due to inadequate purity of the former specimen.

Silver. This was Baker and Company's purest silver obtained from them a number of years ago. It had been subjected to pressure several years ago in the course of exploratory measurements, and again in a preliminary apparatus before the final measurements recorded in the table. The smoothness of the results is not notable, but there was no consistent hysteresis. The deviations from linearity are unsymmetrical, the greatest curvature being in the upper half of the pressure range instead of the lower half, as is more usual when there is any distinction at all. The previous[20] corrected compression at 10,000 on another specimen measured in the 12,000 range was .00946 against .00938 now.

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Silicon. I owe this material to the courtesy of Dr. W. Shockley of the Bell Telephone Laboratories, who in turn obtained it as highly purified material from the laboratories of the Dupont Company. It was subjected to several preliminary applications of 25,000 kg/cm^2 to season. This material probably exhibits some slight hysteresis, but it is mostly swamped by the other irregularities, and the deviations from smoothness have been taken from the mean curve. There are no previous measurements on specimens of sufficient purity to justify comparison.

Beryllium. Measurements were made on only a single specimen. This was a piece of a single crystal, the length being parallel to the cleavage plane (perpendicular to the hexagonal axis), and was the identical specimen as that measured formerly[21] in a narrower pressure range. Unfortunately the specimen in the perpendicular orientation had been broken and no new specimen was available, so that these results are only partial. The specimen was subjected to at least one preliminary application of 30,000. The pattern of deviation from a smooth curve shows definite hysteresis, the width of the loop being about 0.8 per cent of the maximum distortion. However, the deviations were scattered rather less consistently than usual, and the deviation from a smooth curve given in the table (0.41%) is the deviation from the mid-curve of the loop, not the deviation from the branches of the loop separately. The former corrected compression at 10,000 for the identical specimen, measured in the 12,000 range, was .00270 against .00309. The difference is larger than usual; if genuine, it indicates an unusually large effect of increasing the pressure range.

Germanium. This, which was high-purity material of recent manufacture, I also owe to the courtesy of Dr. W. Shockley. It was seasoned by several preliminary applications of 25,000 kg/cm^2. There is undoubtedly some hysteresis in the normal direction, but the irregularities pretty much obscured it, so that no attempt has been made to estimate the width of the hysteresis loop, and the deviation from smoothness reported in the table is the deviation from the mean curve. The previous[22] value for the corrected compression at 10,000 measured on a different specimen in the 12,000 range, was .0136 against .0124 now. The difference is presumably to be ascribed to improved purity in the material.

Aluminum. This was high-purity material obtained a number of years ago from the Aluminum Company of America, through the courtesy of Dr. Greninger. The analysis was: Al 99.966, Cu .022, Fe

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.005, Si .007. It had been subjected to several previous applications of pressure in the course of exploratory measurements some years before these measurements. There was some normal hysteresis discernible in the deviation, but the pattern was not especially consistent and the deviations from smoothness given in the table are calculated from the mean curve. The width of the loop was of the order of 0.5 per cent of the maximum distortion. The previous[23] corrected compression at 10,000 measured on another sample in the 12,000 range was .01290 against .01312 now.

Antimony. The origin of the material was Kahlbaum's high purity metal of the early 1920's. This had been cast into single-crystal form and a selection was made of the pieces still extant. Unfortunately the parallel orientation formerly measured had been fractured and there was none to replace it, the best orientation available being with the length at 8° to the axis. Measurements were made on two specimens, one of the 8° orientation and the other in the 90° orientation (axis perpendicular to the length). From the measured linear compressions in the perpendicular and 8° orientations the compression in the parallel orientation may be readily calculated if it is assumed that the specimen acts like a simple linear element with thickness vanishingly small compared with the length. The formula so obtained is

$$\kappa = \kappa_{8^\circ} + (\kappa_{8^\circ} - \kappa_\perp) \tan^2 8^\circ$$

and this formula was used in computing $(\Delta l/l_0)_\parallel$ as given in the table. Actually, however, the specimen is not a linear element, but the thickness is about a quarter of the length. There is accordingly a change of angle between the ends and the length under the action of pressure, causing the specimen to shear over in such a way as to give too small an apparent compression. This effect is probably negligibly small in the case above, the correction from the 8° to the parallel orientation being small as shown in the table, but for higher orientations the error may be by no means negligible. A set of measurements was actually made on the 49° orientation, and this yielded computed values for the parallel compression smaller by about 15 per cent than the values of the table.

The perpendicular orientation displayed no hysteresis pattern. The 8° orientation, on the other hand, showed a well marked loop with width 1.3 per cent of the maximum distortion. The average deviation from a smooth curve given in the table, 0.48 per cent, was calculated from the mean curve of the loop; it would have been materially less if calculated from the separate branches. The pre-

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vious[24] corrected linear compression at 10,000 kg/cm², measured on similar but not identical material in the 12,000 range, was .00483 for the perpendicular orientation and .01439 parallel, against .00468 and .01498 (the latter calculated) found now.

It is to be noted that the falling off of compressibility with increasing pressure is much greater for the parallel than for the perpendicular orientation. This agrees qualitatively with the former results, the former second degree term for the parallel orientation being five times as great as for the perpendicular direction.

Zinc. New specimens were cut from the remaining stock of single crystal material supplied me by Professor Tyndall in 1935[25] of zinc of unusually high purity, and handled with special care to avoid the strains to which single crystal zinc is particularly susceptible. The compressibility of zinc exhibits a high degree of non-isotropy, the initial compressibility in the parallel orientation (cleavage plane perpendicular to the length) being 8.5 times as great as in the perpendicular orientation. Two sets of measurements were made on the parallel specimen. The pressure range of the first set was only 15,000 kg/cm², higher pressures producing shortening beyond the range of the lever. The specimen was then cut in two and a regular run made to 30,000. The compression at 15,000 on this run agreed within 0.3 per cent with the first run. This orientation showed hysteresis, the width of the loop being 1.6 per cent of the maximum distortion. The nature of the loop and the nature of the irregularities was much like that formerly found[25] in the lower range of 12,000.

The perpendicular orientation (cleavage plane parallel to the length) was not so simple, and more measurements were made on it. Two specimens were first cut from the same original crystal and subjected to the conventional seasoning treatment. Measurement to 30,000 on the two specimens both gave marked cusps or transitions of the second kind, but the character of the deviations from linearity were strikingly different, one specimen giving an unusually large increase of compressibility with pressure, while the other was normal. Repetition on one specimen again gave a pronounced cusp, but now situated at 10,000 instead of at 20,000 kg/cm². Another specimen from another crystal was now prepared with unusual care, and measured immediately in the virgin condition, without the customary seasoning. A second application of 30,000 was then made, and then two sets of measurements during the third and fourth application of 30,000. This specimen showed no such cusps as the others and the results were in fairly close agreement, the extreme difference between different determinations of the linear compression under 30,000 being 0.25

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per cent. Furthermore, the absolute values of the compression with this specimen varied from 2 to 6 per cent less than with the other two specimens. This is the direction in which former experience has shown that internal strains act. For the final result, the mean of the three measurements on the last specimen was used, discarding those on the two others.

These experiments on zinc are instructive in showing that in at least some cases irregularity, non-reproducibility, and discontinuities (transitions of higher orders) may be the result of internal strains and do not necessarily imply impurity.

The former[25] corrected results obtained in the 12,000 range for the linear compression at 10,000 were .01277 and .00154 for the perpendicular and parallel orientations respectively against .01277 (identical) and .00151 found now.

Thorium. This was the identical specimen which was formerly measured, obtained in 1926 from Dr. Rentschler of the Westinghouse Lamp Company. There was no certain hysteresis pattern; the irregularities were mostly confined between 10,000 and 20,000. The former corrected compression at 10,000 obtained from measurements over the 12,000 range was 0.0170 against 0.0173 now.

Tin. The same specimens were used that were formerly measured in the range to 12,000. Neither orientation showed a distinctive hysteresis pattern, and the irregularity was practically the same in the two directions. The previous corrected linear compression at 10,000 was 0.00563 for the perpendicular direction and 0.0632 parallel against .00561 and .00621 now.

Tellurium. The identical specimens were used as in the former[28] measurements. In the parallel orientation there was definitely hysteresis, the width of the loop being 1.5 per cent of the maximum distortion. In the perpendicular direction the hysteresis was slight. The irregularity, measured from the mean curve, was nearly the same for the two orientations. The previous linear compressions at 10,000 in the perpendicular and parallel directions were 0.0222 and − 0.00315 respectively, against 0.00214 and − 0.00390 found now. Especially to be noticed is the negative linear compressibility of this element along the trigonal axis. The deviation from linearity in the pressure for this orientation is also noteworthy.

Alloys and Intermetallic Compounds

Carboloy No. 999. This grade of carboloy is the hardest made by the Carboloy Company, and contains the minimum amount of binder.

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It is the material which I have used for the pistons of my piezometers for reaching 100,000 kg/cm^2, the plastic deformation under simple compression being a minimum. There was probably some slight normal hysteresis, but it was pretty well masked by the general irregularity. There is a slight deviation from linearity of the volume compression, which is 44 per cent of that of iron. Young's modulus for carboloy is about 33 per cent of that of iron. The volume compression was calculated, as always, under the assumption of isotropy, which is perhaps somewhat questionable in view of the method of formation from the powder.

Carboloy No. 905. This is the next hardest grade after No. 999, with somewhat more binder. When used as a piston it shows distinctly more plastic flow. The compression is somewhat greater than that of No. 999 as might be expected from the greater amount of binder (cobalt). A somewhat greater amount of normal hysteresis is discernible than for Grade 999. There is a very slight deviation from linearity of the volume compression in the abnormal direction. There is no reason for supposing that this may not be genuine in view of its physical composition as a sintered product.

Nirex. This alloy is the same as that from which the slide wire of the piezometer is made; its composition has already been given. Measurements were made of the compression in order to determine a small correction in converting piezometer readings to change of length. The specimen measured was from an annealed rod 7/32 inch in diameter furnished by Driver Harris in response to my special request. The lever piezometer was not adapted to measuring the compression of the wire actually used in the piezometer. The specimen was seasoned by a preliminary application of 25,000. There was slight hysteresis in the normal direction, mostly masked by the irregularities. The compression is slightly less than that of iron, but so near to it that the resulting correction is almost negligible.

Stainless Steel "H 26." This stainless steel has the composition: C .094, Mn .36, P .023, S .022, Si .35, Cr 12.26, Ni .46, Mo .50, Cu N.D. I owe it to the courtesy of Dr. A. L. Feild of the Rustless Iron and Steel Corporation, from whom I obtained it a number of years ago. It is the same steel for which data on the effect of pressure in modifying the plasticity have already been published.[29] There is definite hysteresis in the normal direction, the width of the loop being 0.16 per cent of the maximum distortion. The loop is open at the lower end. The deviations from smoothness given in the table are deviations from the separate branches of the loop. The mean com-

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pression of this grade of stainless steel is almost exactly the same as that of pure iron, but the hysteresis characteristics are quite different. The deviation from linearity is in the normal direction.

Martensite. From the metallographical point of view there is considerable interest in finding whether martensite experiences irreversible changes under the action of hydrostatic pressure. Dr. B. L. Averbach of the Department of Metallurgy of the Massachusetts Institute of Technology furnished me with four different specimens of martensite of different thermal treatments. After exposure to pressure these were examined by him by a new method of great sensitiveness to find whether there had been permanent alterations in the dimensions. Other specimens from the same batch I measured for compression in my conventional way. The specimens were all made from the same 1.1 carbon steel. They were all quenched from 1450° F. into iced brine, a treatment which is said to ensure practically 100 per cent martensite in the end product. Four different further treatments were then given to the martensite as thus prepared. The first was the null treatment. The second was refrigerated by holding at − 321° F. for one hour. The third was tempered by holding at + 300° F. for one hour, and the fourth was refrigerated as above, followed by a tempering as above. These four specimens are designated as: Q, QR, QT, QRT. The results for only Q and QRT are reproduced in full in the table. These specimens were measured without preliminary application of pressure in order to reveal any irreversible effects of hydrostatic pressure. None of them showed any measurable permanent change of length, a result which was independently confirmed by Dr. Averbach, and which I believe he intends to make the subject of a special communication elsewhere. All four specimens showed marked hysteresis in the normal direction, far beyond any possible error or irregularity. The deviations from smoothness given in the table are deviations from the two branches of the loop. It will be seen that the smoothness compares favorably with the best of the previous substances, pure iron. The results for specimens Q and QR are practically identical. If anything, the loop for QR is a trifle wider and the absolute compression a trifle less. The width of the loop is approximately 1 per cent of the maximum distortion. The specimen QT is markedly different, the hysteresis loop having narrowed to one-half the width. This process is carried a little further in QRT, the loop being further narrowed, and also altered in shape, the two branches of the loop coalescing up to about 7,000 kg/cm².

It is evident that as far as behavior under hydrostatic pressure

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goes, tempering has a greater effect than refrigerating. The hysteresis is not surprising in view of the fact that martensite is composed of tetragonal crystals, so that under hydrostatic pressure the individual crystals do not deform uniformly in every direction, with resultant development of internal strains.

Before the measurements recorded above on Dr. Averbach's martensite measurements were made on a specimen of commercial drill rod (1.25 per cent C.), quenched and drawn in boiling water. The results were similar, except that the hysteresis loop now was about twice as wide as for the specimen "Q" above.

Stainless Steel "H 29." The composition of this was: C 0.058, Mn 0.70, P 0.030, S 0.013, Si 0.85, Cr 18.51, Ni 8.95, Mo ND, Cu 0.20. Otherwise the same remarks[29] apply as to "H 26." There is marked hysteresis and the deviations from smoothness given in the table are deviations from the branches of the loop. The mean curve is not of the conventional simple shape but is gently S shaped. The volume compressions of the table refer to the mean curve. The maximum width of the loop was 1.16 per cent of the maximum distortion.

Cu_3Au. This was a single crystal which I owe to the courtesy of Dr. Sidney Siegel who prepared it in the Research Laboratory of the Westinghouse Company. It was one of a set of crystals for which he determined[30] the variations of the elastic moduli with temperature. It was subjected to several seasoning applications in the course of early unsuccessful attempts at measurement, at one time reaching a maximum of 30,000 with no permanent change of dimensions, before the measurements recorded in Table II. The hysteresis phenomena are complicated and unusual. The mean curve is S shaped; the loop itself has maximum width at 8,000 and again at 20,000 kg/cm^2, amounting to 1.0 per cent of the maximum distortion. The loop constricts itself to a wasplike waist of vanishing width at 15,000. The deviations from smoothness given in the table are deviations from the mean curve. The hysteresis is in the normal direction, but the initial departures from linearity are in the abnormal direction. There are no previous measurements of compressibility for comparison. Dr. Siegel has, however, calculated from the elastic moduli that the cubic compressibility at 20° is 6.3×10^{-6} (kg/cm^2 units) against 6.0 extrapolated to zero from the above. The agreement is good when consideration is given to the fact pointed out by Dr. Siegel that the calculated compressibility is inaccurate because of the unfavorable values of the moduli, S_{11} being nearly equal to $-2S_{12}$.

Au Zn. This was the identical specimen which had been previously[31]

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TABLE II

COMPRESSION OF ALLOYS AND INTERMETALLIC COMPOUNDS

Pressure kg/cm²	$\Delta V/V_0$										
	Carboloy No. 999	Carboloy No. 905	Nirex	Stainless Steel H26	Martensite (1.1% C) Q Inc.	Martensite (1.1% C) Q Dec.	Martensite (1.1% C) Q.R.T. Inc.	Martensite (1.1% C) Q.R.T. Dec.	Stainless Steel H 29	Cu_3Au	Au Zn
5,000	.00123	.00126	.00276	.00290	.00293	.00300	.00295	.00295	.00301	.00305	.00402
10,000	.00245	.00250	.00543	.00573	.00579	.00592	.00579	.00582	.00599	.00629	.00786
15,000	.00372	.00379	.00811	.00863	.00870	.00895	.00864	.00870	.00901	.00955	.01157
20,000	.00495	.00506	.01071	.01136	.01154	.01166	.01147	.01148	.01195	.01269	.01506
25,000	.00618	.00636	.01325	.01409	.01435	.01442	.01426	.01423	01482	.01572	.01846
30,000	.00737	.00763	.01573	.01676	.01711		.01689		.01757	.01860	.02168
Average percentage deviation from smooth curve	.066	0.80	0.16	0.02	0.018		0.014		0.05	0.27	0.09

Pressure kg/cm²	$\Delta V/V_0$									
	35% Ni 65% Fe	$Cu_{31}Sn_8$	Cu Zn	Ag_2Al	Cu_5Zn_8	Ag Zn	Ag_5Zn_8	Cu_5Cd_8	Sb Sn	Sb_2Tl_7
5,000	.00453	.00451	.00442	.00491	.00527	.00504	.00525	.00632	.0104	.0141
10,000	.00896	.00880	.00873	.00967	.01020	.00991	.01036	.01224	.0198	.0267
15,000	.01337	.01297	.01298	.01436	.01492	.01473	.01541	.01793	.0288	.0383
20,000	.01759	.01689	.01708	.01886	.01938	.01930	.02026	.02333	.0371	.0491
25,000	.02167	.02066	.02106	.02315	.02370	.02369	.02494	.02851	.0448	.0590
30,000	.02459	.02475*	.02487	.02721	.02788	.02790	.02944	.03353	.0522	.0682
Deviation from smoothness	0.26	0.20	0.22	0.29	0.32	0.37	0.18	0.22	0.37	0.17

*Cusp at 25.500

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measured to 12,000. There is well developed hysteresis in the normal direction. The width of the loop is 1.15 per cent of the maximum distortion. The deviations from smoothness given in the table are the deviations from the branches of the loop. The deviation from linearity, which is in the normal direction, is marked. The previous corrected value of compression at 10,000 was .00731 against .00786 found now. The previous measurements to 12,000 disclosed even more marked hysteresis than the present measurements, the width of the loop being 3.6 per cent of the distortion at 12,000.

"*Alloy 121.*" This was a single crystal of composition 35% Ni and 65% Fe which I owe to the kindness of Dr. R. M. Bozorth of the Bell Telephone Laboratories; it was prepared by Mr. H. J. Williams. There is well developed hysteresis in the normal direction, but the loop is not wide, being only 0.49 per cent of the maximum distortion. The deviation from smoothness given in the table, 0.26%, is the deviation from the mean curve. This deviation is almost entirely accounted for by the width of the loop, all the points except one lying unusually close to the branches of the loop. The deviation from linearity is in the normal direction. It is to be noticed that the absolute compression is about 50 per cent greater than would be calculated from either component separately. This is highly unusual; it is normal for the compressibility of an alloy to be less than that calculated by the rule of mixtures from the components.

$Cu_{31}Sn_8$. This was the identical specimen, No. 4, which was previously[32] measured. In the previous work much variation was found in specimens of the material prepared under closely similar conditions. Four specimens were previously measured with an initial compressibility varying from 8.8 to 11.4×10^{-7}. Of these specimens No. 4 was the one with minimum hysteresis and maximum regularity. There is a marked cusp at 25,000 kg/cm^2, $\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ increasing abruptly by 8.7×10^{-9} (kg/cm^2 units) at this point. Below this pressure there is a well marked, but narrow, hysteresis loop in the normal direction of maximum width equal to 0.55 per cent of the maximum distortion. The deviation from smoothness given in the table, 0.20 per cent, is the deviation from the mean curve. The previous corrected compression at 10,000 was .00933 against .00896 now. Considering the character of the material the difference is not surprising.

Cu Zn. This was the identical specimen used in previous[33] measurements to 12,000. The seasoning operation was not adequate, however, for the hysteresis, which was in the normal direction, was un-

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usually large, and furthermore the loop was not closed at the origin. The width of the loop at the maximum was 1.7 per cent of the maximum distortion, and at the open end at the origin 1.5 per cent. The deviations from smoothness given in the table are deviations from the branches of the loop. The deviation from linearity is in the normal direction, but is not as large as might be expected for a substance of this absolute magnitude of compression. This may be connected with the abnormal and open hysteresis. The former corrected compression at 10,000 was .00879 against .00873 now. In the former measurements over the 12,000 range the hysteresis was much larger than above, the width of the loop being 8.5% of the distortion at 12,000. The irregularities formerly found in the 12,000 range were relatively much larger than found now.

Ag_2Al. This is the identical specimen, No. 1, which was formerly[34] measured at 12,000 kg/cm². There is definite hysteresis in the normal direction; the width of the loop is 0.57 per cent of the maximum distortion. The deviations from smoothness given in the table are deviations from the mean curve. Deviation from linearity is normal. The former corrected compression at 10,000 was .00997 against .00967 now. Former measurements were made over an interval of fifteen months and showed considerable secular change in this interval. The initial measurements disclosed a break in the tangent between 5,000 and 6,000; there is now no trace of such a break in the range to 30,000.

Cu_5Zn_8. (Gamma Brass) I owe this to the kindness of Dr. Cyril Smith of the Institute for the Study of Metals of the University of Chicago. The specimen was cut from a larger specimen destined for a study of the effect of hydrostatic pressure on plasticity in tension. The results of this study will be reported elsewhere. There is small hysteresis in the normal direction. The deviations from smoothness given in the table are deviations from the mean curve; the deviation calculated from the branches of the loop is about one-half as great. Deviation from linearity is in the normal direction. The previous[35] corrected compression at 10,000 on another specimen measured over the 12,000 range was .00970 against .01020 now.

$AgZn$. This was the same specimen as previously[36] measured to 12,000. There is definite hysteresis in the normal direction, the width of the loop being 0.87 per cent of the maximum distortion. The deviations from smoothness reported in the table are deviations from the mean curve. Deviation from linearity is in the normal direction. The former corrected compression at 10,000 was .01024 against

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.00991 now. The former measurements in the 12,000 range disclosed much greater irregularities than found now. Part of the difference is doubtless due to slow secular changes in the material as well as the difference of pressure range.

Ag_5Zn_8. This was the same specimen as formerly[37] measured to 12,000. There is no certain hysteresis. However, half the total deviation from smoothness was contributed by the two points at 9,000 and 5,000 on decreasing pressure. These deviated from the smooth curve in the direction of normal hysteresis. Deviation from linearity is normal. The former corrected compression at 10,000 was .01072 against .01036 now. The former measurements showed distinct hysteresis, but on the whole the irregularities were much less than for most of this class of substances.

Cu_5Cd_8. This specimen was formerly[38] measured to 12,000. There is no certain hysteresis. It is not at all improbable that there is a cusp with increase of compressibility near 17,000 kg/cm^2. However, this interpretation depends almost entirely on the evidence of one point, so that I have preferred to smooth the results right over the possible cusp. Should the cusp exist, the effect on the actual relative volume would not produce a difference anywhere of more than 0.00020 compared with the figures given in the table. The former corrected compression at 10,000 was .0137 against .0122 now. The difference is larger than usual.

Sb_2Tl_7. This was the same specimen that had been previously[39] measured to 12,000. The hysteresis was not marked and the regularity was on the whole greater than usual. The previous corrected compression at 10,000 was 0.0296 against 0.0267 now In the former range of 12,000 the regularity of the measurements was also greater than usual.

SbSn. The same specimen was used as in the former[40] measurements to 12,000. There was no obvious hysteresis pattern and the results were in no way noteworthy. The former corrected compression at 10,000 was 0.0202 against 0.0198 now. The former measurements in the range to 12,000 were smoother than usual.

Minerals

A. Minerals Crystallizing in the Cubic System

Garnet. This specimen has been previously[41] measured to 12,000. There is small hysteresis in the normal direction; the width of the loop is 0.62 per cent of the maximum distortion. The deviations from

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smoothness in the table are deviations from the mean curve. The former corrected compression at 10,000 was 0.00538 against 0.00529 now.

Mg O. This was a water-clear single crystal. It had been previously[42] measured to 12,000. There is distinct hysteresis in the normal direction; the width of the loop is 0.89 per cent of the maximum distortion. The deviation from smoothness given in the table, 0.18 per cent, is the deviation from the mean curve. The points lie with unusual smoothness on the branches of the loop, and if the deviations had been calculated from the two branches instead of the mean, a smoothness equal to that of the best of the former specimens would have been found. The former corrected compression at 10,000 was .00579 against .00571 now. Various small irregularities were formerly found in the range to 12,000 which were ascribed to a failure of a "perfect state of ease." These effects are here diminished by seasoning through a wider pressure range, which seems natural.

Magnetite. This was the larger of two pieces formerly[43] measured to 12,000. There is perhaps just perceptible hysteresis in the normal direction, but it is too small to attempt to estimate numerically. There is a cusp at 22,500 kg/cm² with increase of $-\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ by 2.8×10^{-8} (kg/cm² units). The former corrected compression at 10,000, measured on two pieces stacked together, was .00532 against .00564 now.

Andradite. This has been previously[41] measured to 12,000. There is a cusp at 22,500 with increase of $-\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ by 1.09×10^{-7} (kg/cm² units), an unusually large change, which amounts to about one sixth of the total $\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$. The existence of the cusp was checked by repetition of the measurements both with increasing and decreasing pressure over the region of the cusp. Furthermore, there is hysteresis in the normal direction, the width of the loop amounting to 0.66 per cent of the total distortion. On repetition the points fell on the same loop as with the first measurement, thus checking the genuineness of the hysteresis and the adequacy of the seasoning. The previous corrected compression at 10,000 was .00653 against .00636 now.

Pyrite. This was the second of two specimens which had been previously[43] measured to 12,000. There is hysteresis somewhat confused by the irregularity of the points. The width of the loop is of

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TABLE III

COMPRESSION OF CUBIC MINERALS

Pressure kg/cm²	$\Delta V/V_0$								
	Garnet	Mg O	Magnetite	Andradite	Pyrite	Cobaltite	Fluorite	Li F	Galena, PbS
5,000	.00272	.00290	.00286	.00325	.00328	.00353‡	.00585	.00712	.00936
10,000	.00538	.00571	.00564	.00636	.00645	.00702‡	.01147	.01406	.01792
15,000	.00807	.00859	.00845	.00947	.00963	.01087§	.01695	.02068	.02602
20,000	.01071	.01139	.01118*	.01248†	.01282	.01444§	.02213	.02696	.03363
25,000	.01333	.01410	.01394*	.01542†	.01575	.01753	.02735	.03302	.04074
30,000	.01588	.01674	.01670	.01852	.01869	.02050	.03234	.03861	
Average Percentage Deviation from Smooth Curve	0.23	0.18	0.16	0.35	0.27	0.24	0.22	0.41	0.94

*Cusp at 22,500 †Cusp at 22,500 ‡Cusp at 9,500 §Cusp at 18,500

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the order of 0.50 per cent of the maximum distortion. The deviations from a smooth curve given in the table are deviations from the mean curve. The previously measured corrected compression of this specimen at 10,000 was .00662 against .00645 now.

Cobaltite. This had been previously[43] measured to 12,000. There are two cusps. At the lower, at 9,500 kg/cm^2, $-\frac{1}{v_0}\left(\frac{\partial v}{\partial p}\right)_\tau$ increases discontinuously by 6.8×10^{-8} (kg/cm^2 units), and at the second, at 18,500, it decreases discontinuously by 1.12×10^{-7}. Between the two cusps the readings with increasing and decreasing pressure differ by 1.39 per cent of the maximum distortion. The difference between the increasing and decreasing readings is in the direction to correspond to a normal hysteresis. There is not, however, a proper loop, but the difference is nearly constant over the range. The deviations from smoothness given in the table are calculated on the mean curve. The previous corrected compression at 10,000 was .00739 against .00702 now. No cusp was previously found; this may well be an effect of the difference of range.

Fluorite. This was previously[43] measured to 12,000. Any hysteresis is somewhat obscured by the general irregularity of the points. What hysteresis there is, is in the normal direction, and the width of the loop is of the order of 0.4 per cent of the maximum distortion. The deviations from smoothness given in the table are calculated from the mean curve. The previous corrected compression at 10,000 was .01148 against .01147 now. The agreement is fortuitous.

LiF. This was a water-clear single crystal prepared in this laboratory a number of years ago by Dr. E. G. Schneider, and was the same specimen that was previously[44] measured in the 12,000 range. There was no definite hysteresis. The previous corrected compression at 10,000 was 0.0143 against 0.0141 now.

Galena. (*PbS*). This was the same specimen as previously[43] measured to 12,000. Galena has already been found[45] to have a transition in the neighborhood of 25,000. This transition was again found here, so that the measurements above 25,000 were without special significance. This transition is apparently one of those which run without drastic rearrangement of the lattice, the original lattice being recovered after the reverse transition runs. This was suggested by there being no permanent change of length, by the approximate coincidence of the pressure points with increasing and decreasing pressure after the occurrence of the transition, and by the unaltered

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appearance of the specimen, in which the reflection pattern was unusually prominently developed. As a further check, the specimen was destroyed after the measurements by cleaving it, to find whether there had in fact been any change in the actual cleavage. It was found that in fact the location of the cleavage plane was unchanged, thus checking the above characterization of the transition. But in making the cleavage, a small inclusion of some white foreign substance was found, which was entirely unsuspected from the unusually sound appearance of the exterior. This inclusion doubtless introduces some error, probably small, into the absolute value for the compression, and more importantly is probably responsible for the unusually large irregularity in the results. Any conventional hysteresis was masked by the irregularities. The former value for the corrected compression at 10,000 was 0.0178 against 0.0179 now. In the former measurements the specimen was presumably virgin, not having experienced the transition. At least it had not experienced it in the laboratory, and the pressure of the transition would demand a depth of origin in the earth such that it probably had not occurred in nature.

B. Non-Cubic Minerals

Al_2O_3 (*Sapphire*). This was new synthetic material which I owe to the courtesy of the Linde Air Products Co. The specimens were cut from single rods, grown by their well-known method. Two orientations were measured, one with the c axis at 90° to the length, and the other with the c axis at 10° to the length. It would have been desirable if the 0° orientation could have been measured, but low orientations do not often occur, and considerable search was necessary to find a suitable specimen with orientation as low as 10°. In addition to the control on orientation, the specimens were selected for freedom from internal flaws, which usually take the form of minute bubbles. The rods were subjected to examination with a low-power microscope and specimens found which appeared almost completely free from imperfections. After selection, they were centerless ground in order that the external surface should be cylindrical.

Six sets of measurements were made on the 90° orientation and two on the 10°—more than on most substances. The results given in the table are means of all the runs, each run being weighted inversely according to the average deviation of its single points from a smooth curve. The material showed no tendency to settle down to a smooth final behavior, but the irregularities persisted through all the runs. This is no doubt a consequence of imperfect homogeneity. It has already been found[46] that the mechanical strength of this material is subject to wide and capricious variation. Although the former

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material was not as carefully selected as this and complete freedom from visual flaws was not attained, there is no reason to think that complete freedom from flaws of every scale was attained with the present specimens.

It will be noticed that the linear compression is very nearly the same in the two orientations. The formulas are well known for calculating the compression in the 0° orientation from the compressions at 90° and 10°. The correction from 10° to 0° is very small, being at most unity in the next place of decimals beyond the last listed in the table. From the linear compressions at 90° and 0° the volume compression was computed.

The deviations from linearity are small and in the normal direction. Within experimental error, the linear compression in the two orientations was a quadratic function of pressure.

Al_2O_3 has been previously[47] measured to 12,000. The former specimens were cut from a large boule which was unusually free from the large internal strains which make nearly all boules fracture spontaneously when cut. The former specimen showed marked anomalies below 12,000. In the 0° orientation there were marked cusps at room temperature and 75°, and in the 90° orientation a less well marked cusp at 75°. These small effects are with high probability the results of small internal strains. The absolute compression found before was not greatly different from that found now. The linear compression at 10,000 kg/cm^2 found formerly for the 0° orientation was 0.00111 against 0.00118 found now, and for the 90° orientation 0.00104 found formerly against 0.00119 found now. The present results, because of the freedom from marked anomalies, are certainly to be preferred to the former values as being closer to the probable values for the perfect Al_2O_3 lattice.

Beryl. This has been previously[41] measured to 12,000 in the parallel and perpendicular orientations. There is definite hysteresis in the normal direction for both orientations, the width of the loop being 1.2 per cent of the total distortion for the parallel orientation, and 1.4 per cent perpendicular. The individual points lie with great smoothness on the two branches of the loops, the deviations from smoothness given in the table are the deviations from the mean curve; the deviations from the branches of the loop could be about one quarter as much. The corrected changes of length at 10,000 formerly found were 0.00202 and 0.00161 for the parallel and perpendicular orientation respectively, against 0.00199 and 0.00155 found now.

Note the abnormal increase of compressibility in the perpendicular orientation.

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Topaz. This crystallizes in the orthorhombic system, so that three specimens at right angles to each other are required. The same specimens were used that had been previously[41] measured to 12,000.

All three orientations showed a cusp at 26,000 kg/cm^2 with discontinuous *decrease* of linear compressibility, $-\frac{1}{l_0}\left(\frac{\partial l}{\partial p}\right)_\tau$. This discontinuous decrease was 1.55×10^{-8} for the A orientation, 1.68×10^{-8} for the B, and 1.96×10^{-8} for the C. It could not be maintained, I think, that these differences are significant, and that the discontinuity is not really the same within experimental error for the three orientations. It is to be remarked that the state of affairs is here entirely unlike that of $NiSO_4\ 6H_2O$, for example, in which there is a very marked cusp in one direction but none at right angles to it.[4]

Below the cusp, the A and C orientations show hysteresis in the normal direction which is doubtless beyond experimental error, but the B orientation shows nothing which is not masked by the irregularity of the points. The loops for the A and C orientations are closed at the origin, but open at the cusp end. The maximum width of the loops was 0.75 and 0.50 per cent of the total distortion respectively. The deviation from smoothness given in the table is in all cases the deviation from the mean curve.

The former corrected values for the linear compression at 10,000 kg/cm^2 for the A, B, and C orientations are 0.00211, 0.00145, and 0.00228, respectively, against the former values 0.00210, 0.00144, and 0.00217. It is to be considered whether the alteration in the value for C is the result of the greater pressure range and a permanent change on passing through the cusp.

Spodumene. This mineral has been previously[41] measured to 12,000. It crystallizes in the monoclinic system, so that four orientations are required to completely determine the effect of hydrostatic pressure. The *b* and the *Y* orientations both show hysteresis in the normal direction, but the loop is so obscured by the irregularity that I did not think it worth while to attempt to estimate its width. In the *c* orientation there is no evident hysteresis, and the points are of an unusual regularity. In the *a* orientation the loop width is 0.8 per cent of the maximum distortion. The deviation of the individual points from the branches of the loop is 0.09 per cent, as against 0.37 per cent when measured from the mean curve.

In calculating the volume change given in the table it was assumed that this could be computed with sufficient precision from the *b*, *c*, and *Y* orientation by the formulas applicable to orthorhombic crystals. The corrected linear compressions at 10,000 kg/cm^2 formerly found for

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the a, b, c, and Y orientations were 0.00177, 0.00242, 0.00197, and 0.00239 respectively against 0.00176, 0.00252, 0.00189, and 0.00225 found now. Formerly the Y orientation showed the greatest deviation from linearity (in the normal direction); now it is the b orientation.

Tourmaline. The same two specimens of black tourmaline were used as in the former[41] measurements to 12,000; these were parallel and perpendicular to the trigonal axis. There were small abnormalities in the behavior of this material in both orientations. In the parallel orientation there is no conventional hysteresis, but a literal acceptance of the irregularities indicates a saw-tooth pattern in the deviations from a smooth curve, there being four episodes between atmospheric pressure and 30,000. The amplitude of these excursions is small, however, the average deviation from the smooth curve drawn through the midst of the experimental points being only 0.6 per cent. In the perpendicular orientation there is definite hysteresis, the width of the loop being 2.3 per cent of the maximum distortion. The individual points, unlike the parallel orientation, lie smoothly on one or the other branch of the loop, with a mean deviation from the branches of the loop of 0.18 per cent, whereas the average deviation from the mean curve through the loop is 0.6 per cent. The shape of the loop differs somewhat from the canonical, the maximum width of the loop being near 20,000, with a drawn-out tail at the low-pressure end.

The former corrected compressions at 10,000 for the parallel and perpendicular orientation were 0.00465 and 0.00158 respectively against 0.00484 and 0.00185 found now.

Apatite. This crystallizes in the hexagonal system, so that two orientations are necessary. The same parallel and perpendicular specimens were measured here that were formerly[41] measured. In the perpendicular direction the hysteresis phenomena are normal, the width of the loop being 0.77 per cent of the maximum distortion. The hysteresis is not well marked above 20,000. In the parallel direction the hysteresis loop is distinctly S-shaped, so that the deviation from linearity is abnormal and cannot be reproduced by a quadratic expression. The width of the loop at the maximum for this orientation is 1.52 per cent of the maximum distortion. The deviations from smoothness given in the table for both orientations are deviations from the mean curves. The former measurements gave for the corrected linear compressions at 10,000 kg/cm^2 for the parallel and perpendicular orientations 0.00241 and 0.00396 against 0.00240 and 0.00398 respectively found now. Both sets of measurements

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agree in giving an abnormally small deviation from linearity to the parallel orientation.

Mica. The results for this are only rough. The chief interest in attempting the measurements at all was to know the order of magnitude of the corrections introduced by the compression of the mica insulation in various pieces of my high pressure apparatus. Mica is monoclinic, so that, in principle, specimens should have been measured in four orientations. Because of the very pronounced cleavage it would have been exceedingly difficult to cut and handle all these orientations and I contented myself with measuring the linear compression in a single orientation cut parallel to the main cleavage plane at an undetermined angle in that plane and also the mean volume compression to 40,000 kg/cm^2 in the apparatus described in a previous paper.[48] The precise variety of mica was not known; the specimen was cut from a nugget from the University Museum about 2 cm. in diameter and 1 cm. thick, with a distorted hexagonal cross-section evidently corresponding to the outline of a single crystal. The thin sheets were nearly perfectly transparent, of a light brown cast.

The linear compression measurements on the orientation parallel to the cleavage plane disclosed an unusually well marked cusp at 19,500 kg/cm^2, with an abrupt drop in $-\frac{1}{l_0}\left(\frac{\partial l}{\partial p}\right)_\tau$ of approximately 8×10^{-8}. Below the cusp there is also marked hysteresis in the normal direction, the width of the loop being 2.2 per cent of the maximum distortion.

If it is assumed that the linear compression is approximately the same for all orientations in the cleavage plane, it may be calculated that the linear compressibility perpendicular to the cleavage plane is approximately twice as great as in the plane. This is the direction of variation to be expected.

Celestite. This has been previously[43] measured to 12,000. It belongs to the orthorhombic system, so that three orientations are required. The a orientation shows irregularity and hysteresis below 15,000, but is perfectly smooth above. The b and c orientation show hysteresis in the normal direction, normally distributed over the entire pressure range. The width of the loop for the b orientation was 0.52 per cent of the maximum distortion, and that of the c orientation 0.38 per cent. The deviations from smoothness given in the table are deviations from the mean curve. The former values for the corrected linear compression at 10,000 kg/cm^2 were 0.00596, 0.00425, and 0.00440 for the a, b, and c orientations respectively against 0.00588, 0.00418, and 0.00423 found now. The present

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results agree with the former ones in giving the greater departure from linearity (normal direction) to the b orientation.

Barite. This is orthorhombic, so that three orientations are required. It has been previously measured[41] to 12,000. Of the former specimens only that in the A orientation was available, so that it was necessary to cut new specimens from other crystals. In the cutting some confusion arose with regard to orientation, so that more specimens were measured to 30,000 than would otherwise have been necessary. Six specimens were measured; these comprised the original A orientation, the A, B, and C orientations from the same new crystal, described by Professor Frondel to whose kindness I owe it as the best barite crystal he had ever seen, and two other specimens in the B orientation from two other crystals. The orientations were checked by Professor Frondel after the measurements. In Table IV the results are shown for the three orientations all cut from the same good new crystal. This showed no hysteresis. The former corrected compressions at 10,000 for the A, B, and C orientations were 0.00461, 0.00630, and 0.00532 respectively against 0.00478, 0.00634, and 0.00498 found now. The new result at 10,000 on the identical former A specimen was 0.00465 against 0.00461, thus checking the method. The outstanding differences are therefore to be ascribed to variation of the material from crystal to crystal. The two other B specimens from two other crystals gave at 10,000 and 30,000 0.00674 and 0.00656 and 0.01778 and 0.01745 respectively. The extreme variation at any pressure to be ascribed to the material is about 6 per cent. The deviation of the linear compression from linearity in the pressure is about three times as great in the A direction as in C.

Hanksite. This mineral is described in Dana as belonging to the hexagonal system, with the composition $9Na_2SO_4.2Na_2CO_3.KCl$. The same specimen in the perpendicular orientation was used as in the former[41] measurements to 12,000; the parallel orientation was a new specimen cut from the original crystal. In neither orientation was there marked hysteresis, but the scattering of the points was greater than usual in the parallel orientation. The previous corrected compressions at 10,000 were 0.01040 and 0.00574 for the parallel and perpendicular directions respectively against 0.01020 and 0.00738 now. The discrepancy in the perpendicular direction is not obviously explainable and would suggest a blunder somewhere. There were a few minor flaws in the specimen, but nothing large enough to account for any such difference.

Quartz. The same two specimens were used as in the former[41]

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TABLE IV

COMPRESSION OF NON-CUBIC MINERALS

Pressure kg/cm²	Al_2O_3			Beryl			Topaz			
	$\left(\frac{\Delta l}{l_0}\right)_{90°}$	$\left(\frac{\Delta l}{l_0}\right)_{10°}$	$\Delta V/V_0$	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_A$	$\left(\frac{\Delta l}{l_0}\right)_B$	$\left(\frac{\Delta l}{l_0}\right)_C$	$\frac{\Delta V}{V_0}$
5,000	.00060	.00059	.00178	.00100	.00077	.00254	.00106	.00072	.00108	.00285
10,000	.00119	.00118	.00355	.00199	.00155	.00509	.00210	.00144	.00217	.00570
15,000	.00179	.00179	.00537	.00299	.00242	.00781	.00317	.00218	.00331	.00863
20,000	.00238	.00239	.00704	.00398	.00320	.01033	.00421	.00291	.00443	.01150
25,000	.00297	.00300	.00891	.00496	.00404	.01297	.00525	.00366	.00555	.01439
30,000	.00355	.00360	.01067	.00585	.00486	.01550	.00622*	.00448*	.00658*	.01718
Average Percentage Deviation from Smooth Curve	0.49	0.93		0.25	0.50		0.24	0.31	0.19	

*Cusp at 26,000

Pressure kg/cm²	Spodumene					Tourmaline		
	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\left(\frac{\Delta l}{l_0}\right)_Y$	$\left(\frac{\Delta V}{V_0}\right)$	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$
5,000	.00088	.00128	.00095	.00114	.00337	.00245	.00094	.00431
10,000	.00176	.00252	.00189	.00225	.00663	.00484	.00185	.00851
15,000	.00265	.00375	.00283	.00338	.00993	.00715	.00273	.01257
20,000	.00353	.00495	.00375	.00448	.01312	.00937	.00359	.01647
25,000	.00442	.00610	.00466	.00557	.01624	.01147	.00444	.02023
30,000	.00529	.00719	.00556	.00663	.01925	.01336	.00525	.02368
Average Percentage Deviation from Smooth Curve	0.37	0.48	0.05	0.46		0.6	0.6	

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TABLE IV (Continued)

COMPRESSION OF NON-CUBIC MINERALS

Pressure kg/cm²	Apatite			Mica		Celestite			
	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_{\text{parallel cleavage}}$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\frac{\Delta V}{V_0}$
5,000	.00121	.00203	.00525	.0013	.0049	.00296	.00215	.00215	.00725
10,000	.00240	.00398	.01032	.0028	.0092	.00588	.00418	.00423	.01423
15,000	.00362	.00592	.01539	.0042	.0165	.00861	.00612	.00629	.02088
20,000	.00484	.00779	.02028	.0058*	.0227	.01134	.00795	.00825	.02729
25,000	.00603	.00963	.02508	.0070	.0311	.01377	.00973	.01017	.03330
30,000	.00716	.01139	.02964	.0082	.0353	.01623	.01151	.01198	.03920
Average Percentage Deviation from Smooth Curve	0.40	0.39		0.46		0.24	0.20	0.30	

* Cusp at 19.500

Pressure kg/cm²	Barite				Hanksite			Quartz		
	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\left(\frac{\Delta l}{V_0}\right)$	$\left(\frac{\Delta}{l_0}\right)_{\parallel}$	$\left(\frac{\Delta l}{l_0}\right)_{\perp}$	$\frac{\Delta V}{V_0}$
5,000	.00247	.00323	.00251	.00819	.00523	.00369	.01256	.00334	.00480	.01289
10,000	.00478	.00634	.00498	.01601	.01020	.00738	.02476	.00642	.00909	.02440
15,000	.00696	.00934	.00740	.02351	.01455	.01073	.03558	.00920	.01308	.03495
20,000	.00895	.01222	.00973	.03058	.01843	.01379	.04531	.01170	.01688	.04478
25,000	.01076	.01495	.01204	.03728	.02196	.01662	.05419	.01406	.02056	.05418
30,000	.01243	.01748	.01427	.04354	.02522	.01927	.06241	.01622	.02411	.06308
Average Percentage Deviation from Smooth Curve	0.79	0.39	0.94		1.1	0.30		0.28	0.42	

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measurements to 12,000 of 1924–25. Neither orientation showed definite hysteresis. The former corrected compressions at 10,000 for the parallel and perpendicular orientations were respectively 0.00644 and 0.00901 against 0.00642 and 0.00909 now.

Organic Crystals

Finally, results are given for three organic crystals, only one with a complete set of orientations. Many organic crystals are soluble in the ordinary pressure transmitting medium, so that special methods have to be employed. The three measured here do not suffer from this difficulty and were such that they could be easily measured with the apparatus at hand. In general, the absolute values of the compressions of organic substances may be expected to be materially greater than that of the other substances of this paper, and the departure from linearity correspondingly greater.

Sucrose. (Cane Sugar). This crystallizes in the monoclinic system, requiring four compression specimens. The same specimens were used as in the previous[49] measurements to 12,000. There is nothing particularly noteworthy about the results. No direction exhibited definite hysteresis, and the deviation from a smooth curve was normal enough. The previous corrected compressions at 10,000 were 0.0257, 0.0119, 0.0183, and 0.0241 for the a, b, c, and Y directions respectively, against 0.0258, 0.0120, 0.0187, and 0.0254 found now. The volume decrement listed in Table V was calculated from the linear compression in the b, c, and Y directions.

TABLE V

COMPRESSION OF ORGANIC SINGLE CRYSTALS

Pressure kg/cm²	Sucrose					Rhamnose		Gulonic Lactose
	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_b$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\left(\frac{\Delta l}{l_0}\right)_Y$	$\frac{\Delta V}{V_0}$	$\left(\frac{\Delta l}{l_0}\right)_a$	$\left(\frac{\Delta l}{l_0}\right)_c$	$\left(\frac{\Delta l}{l_0}\right)_b$
5,000	.01420	.00662	.01052	.01469	.03151	.01621	.00600	.01586
10,000	.02581	.01202	.01873	.02542	.05518	.02968	.01047	.02784
15,000	.03435	.01677	.02516	.03426	.07434	.04102	.01416	.03753
20,000	.04149	.02097	.03087	.04170	.09074	.05036	.01692	.04588
25,000	.04814	.02480	.03618	.04838	.10552	.05888	.01806	.05411
30,000	.05323	.02831	.04084	.05443	.11866	.06598	.02052	.05870
Deviation	0.34	0.49	0.43	0.39		0.71	0.92	0.48

Rhamnose. This is also monoclinic, requiring four orientations, but only two of the former[50] specimens were still available, those in the a and c directions. In the a orientation there was definite hysteresis in

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the normal direction, the maximum width of the loop being 1.43 per cent of the maximum distortion. In the c direction there was no definite hysteresis. The previous corrected compressions at 10,000 were 0.02921 and 0.01041 for the a and c orientations respectively, against 0.02968 and 0.01047 found now.

Gulonic Lactose. This is orthorhombic. Of the three former[41] specimens only that in the b direction was now available. There is no definite hysteresis. The former corrected compression at 10,000 for this orientation was 0.0268 against 0.0278 now. The deviation from linearity of this substance is unusually large.

Summary and Discussion

A chief result of the extension of precise and sensitive measurements of compressions to 30,000 kg/cm² has been a change in my physical intuition of what to expect. It must still, I think, be accepted as inherently probable that a truly homogeneous substance exposed to a truly hydrostatic pressure can only respond in a smooth fashion, without permanent alteration of dimensions after release of pressure and without hysteresis, and in general with a strain which is a single-value function of pressure. The new insight is that as a matter of fact such completely homogeneous materials are not easy to find, but the majority of substances contain imperfections of one sort or another, perhaps as imperfections of the pure lattice, perhaps as chemical inhomogeneities between the grains, which give rise to small-scale capricious irregularities in their response to pressure in addition to a more or less consistent small-scale hysteresis. The development of such a response would be expected to be more marked the greater the pressure range and the greater the perfection of the measurements. Both of these factors doubtless conspire to make the effects so much more noticeable in the present range of 30,000 kg/cm² than in the former range of 12,000.

Acceptance of this point of view demands consideration of one important factor, namely whether the irregularities may not be due to a failure of the pressure to be adequately hydrostatic in the new range because of the very rapidly increasing viscosity under pressure which liquids, especially those with complicated structures, are known to exhibit. A satisfactory answer to this question is possible only now that a quantitative measurement has been made of the viscosity of the transmitting liquid, a mixture of n- and i-pentane, up to 30,000. The results of these measurements, together with those on other liquids, are being published in another number of these Proceedings. It was found that the absolute viscosity of i-pentane

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at room temperature at 30,000 kg/cm^2 is about 170 poises. This is about four times the viscosity of glycerine under ordinary circumstances. In view of the slowness with which changes of pressure are produced, about five minutes being consumed in pumping to the final pressure, and the very low corresponding flow velocities in the transmitting liquid which arise only from the volume compression, I believe that any failure of pressure to be truly hydrostatic can now be confidently ruled out as a pertinent factor.

The nature of the hysteresis requires comment. Under normal conditions "hysteresis" by its very derivation signifies a lagging of the effect behind the cause. Under our conditions this would mean that with increasing pressure the decrement of length for a fixed pressure would be numerically less than the decrement under the same decreasing pressure. Although this sort of relationship appears most natural, and is what has been called "normal" above, there is no necessity for it, particularly in those cases where the analysis of the phenomenon into a "cause" and an "effect" is not inevitable. The only necessity would seem to inhere in those situations in which energy relations are involved. Hysteresis may involve an expenditure of energy, and if the coordinates are properly chosen, the area of the hysteresis loop may represent the energy involved in a cycle. Since we are supposing that a steady state is involved, the energy is thermal and the cycle must be dissipative by the second law of thermodynamics. Therefore, if in the steady state there is hysteresis between the *volume* and the pressure, the sense of the hysteresis loop must be "normal." There is, however, no necessity that hysteresis between *length* and pressure should have the normal sense, and in the measurements above, at least four examples were found of an abnormal sense: single crystal tungsten, ruthenium, gold, and columbium. Even in these cases, however, the volume hysteresis must have had the normal sign, so that one can draw the conclusion that these four metals were not isotropically deformed by hydrostatic pressure, but that the hysteresis of the transverse dimensions must have been in the other sense and sufficient to at least compensate the longitudinal hysteresis.

In addition to the irregularities and hysteresis a number of the substances showed cusps or transitions of "the second kind" in the notation of Ehrenfest. These I think must be accepted as an entirely different sort of thing, truly characteristic of the material. The substances which showed these cusps were: nickel, palladium, $Cu_{31}Sn_8$, magnetite, andradite, cobaltite, topaz, and mica. The explanation of these cusps is a task for the theoretical physicist. It is natural to suspect some magnetic effect in the case of nickel and magnetite. In

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developing the theory for noncubic crystals it is important that we now have examples both where the discontinuity of derivative is confined to a single direction and where it affects all directions.

It has already been intimated that the irregularities and hysteresis obscure the deviations from linearity that must be supposed to characterize the ideally homogeneous material. In the case of substances with a normal hysteresis loop of the typical lens shape, the best that can be done is doubtless to use the mid-curve of the loop as characterizing the homogeneous material. It seems probable that there is not much danger in doing this. But in the few cases where the loop has some non-typical shape, the best procedure is not obvious. It is to be remarked that embarrassment from this arises in comparatively few cases. Serious uncertainty arises only in the case of materials like some of those examined in this paper in which the deviations from linearity are small because of the absolutely small values of compressibility, and in which irregularities due to inhomogeneities are comparatively large because of the mechanical hardness that usually accompanies incompressibility. Even for these materials the hysteresis loop has the typical lens shape in most cases. The great majority of substances are like those which have been examined in previous papers, in which the compressibilities are higher, the deviations from linearity greater, and the capricious irregularity and hysteresis so much less comparatively, because of the greater mechanical softness, as to occasion little uncertainty as to the correct values for the higher order terms in the compression.

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LYMAN LABORATORY OF PHYSICS
Harvard University, Cambridge, Mass.

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A "FREE MANOMETER" TECHNIQUE FOR USE WITH THE WARBURG APPARATUS

Avram Goldstein

From the Department of Pharmacology, Harvard Medical School, Boston, and the Marine Biological Laboratory, Woods Hole, Massachusetts.

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A "FREE MANOMETER" TECHNIQUE FOR USE WITH THE WARBURG APPARATUS

AVRAM GOLDSTEIN*

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INTRODUCTION

The Warburg apparatus, as commonly employed, is based upon a gas reaction occurring within a closed system of known and constant volume. Pressure changes are read directly on the open side of the manometer, the temperature being held constant. Under these conditions, assuming that the gas laws apply, the pressure change is a *linear function* of the volume (or moles) of gas evolved or taken up. This function is known as the "vessel constant" and depends upon gas volume, fluid volume, temperature, solubility of the reacting gas, atmospheric pressure, and manometer fluid density.[1] The linearity of the relationship *appears* to require that the gas volume be held constant, and this can only be achieved by repeatedly levelling the fluid on the vessel side of the manometer to a predetermined mark. That the levelling procedure is inconvenient, and productive of certain errors and limitations, will be evident to those who have employed the apparatus extensively.

In the modification to be described, the manometer fluid is not levelled during a reaction; i. e., both pressure and volume are allowed to vary. The fluid on the *vessel side* of the manometer is set initially to the manometer midpoint (150 mm.) and subsequent readings are then made on this same arm of the manometer. The manometer fluid adjustment is never touched again after the initial setting. A reciprocal and equal change occurs in the fluid levels in the two arms as a reaction proceeds, but the fluid in the open arm is ignored. Thermobarometer corrections are made as usual (for certain limitations see p. 243) and the readings multiplied by vessel constants in the customary fashion, to obtain micromoles (or cu. mm.) gas at NTP.

In justification of this procedure we shall show that in the Warburg apparatus a constant volume is *not* the necessary condition for a linear function relating pressure change to evolved (or absorbed) gas; that, on the contrary, when both pressure and volume are allowed to vary, a linear function is still obtained, within the limits of accuracy

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of the method (1%); and that, consequently, the levelling operation can be omitted.

This "free manometer" technique offers the following points of difference from the constant volume method:

(1) Since nothing need be adjusted during a reaction, automatic recording—as by a time-controlled camera—becomes feasible.

(2) The error introduced by the levelling procedure itself is eliminated. We refer to the small differences in pressure readings upon repeated levelling of the meniscus, the result of unavoidable inaccuracies in the performance of this operation.

(3) The error introduced by levelling immediately before a reading is eliminated. We refer here to the transient pressure change resulting from a sudden change in the gas space as the fluid is levelled, and before the new gas-fluid equilibrium is established. Although the errors cited here and in the paragraph above are small, their reality can be readily confirmed.

(4) Readings can be made more rapidly and more frequently, since the time consumed by the levelling operation is eliminated. This is especially welcome when one wishes to follow the first few minutes of a reaction, or when a reaction is proceeding so rapidly that considerable change occurs while the usual seven manometers are being read. If one reads to no better accuracy than 1 mm., it is perfectly satisfactory to read the manometers in motion.

(5) The capacity of the standard manometer is substantially increased while its sensitivity is correspondingly reduced. Thus on the one hand it becomes possible to measure a total gas change three to four times as great as by the standard method, without resetting the manometer; on the other hand small quantities of gas cannot be detected as well or measured as accurately. Whether capacity is preferable to sensitivity will depend upon the circumstances, and there are certain applications for which the former proves more desirable than the latter. Two such cases where we have found the method decidedly useful are studies of the time course of enzyme-substrate reactions and measurement of substrate oxidation by bacteria in the presence of a high endogenous respiration. We have calculated the vessel constants for both methods and find it convenient to use the free manometer technique as a matter of course, reserving the constant volume method for those occasions when a high sensitivity is desired.

(6) As against the advantages cited must be weighed the drawback of a somewhat more complex equation for the calculation of vessel constants. Besides calibrating the vessel volume one must also determine the linear volume of the manometer (cu. mm. per mm.).

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This, however, need not involve an additional operation if one follows the calibration method suggested by Burris,[2] (p. 50), filling the manometer first to a point above, and then to a point below the 150 mark. If one determines the constants empirically, these problems are, of course, irrelevant. As will be seen shortly, the constants are not quite so readily transformed for changed conditions of temperature or fluid volume as in the constant volume method.

General Theory of the Method

A. *The relation of pressure change to volume change.*

Although pressure and volume both vary, a fixed relationship is imposed by the fact that manometer fluid is neither added nor removed during a reaction. Thus (see figure 1), $\Delta p = 2\Delta h$ and $\Delta v = M\Delta h$, where M, the manometer factor, is cu. mm. per mm. manometer.

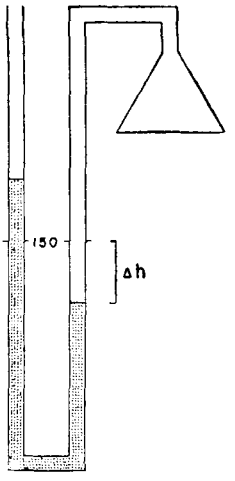

FIGURE 1.

B. *The complete equation.*

We shall develop the vessel constant equation for the case of a reacting gas, x, and an inert gas, z, both present. The full equation is not linear, but we shall show that by making certain legitimate simplifications it can be transformed to linear form.

Let P_0 = initial total pressure (atmospheric), expressed in mm. manometer fluid = 10,000 mm. when manometer fluid density is 1.033.

P_w = vapor pressure of water at temperature T (absolute).

P_x, P_z = initial partial pressures of the gases.

P_x', P_z' = final partial pressures of the gases.

α_x, α_z = solubility coefficients (moles per cu. mm. at P_0, T).

V = initial gas space (cu. mm.).

V_f = fluid volume (cu. mm.).

M = manometer factor (cu. mm. per mm.).

R = gas constant (8.21×10^8 cu. mm. atm. [mm. manom. fluid] $\times$ deg.$^{-1}$ $\times$ mole^{-1}).

Δv = change in gas volume.

Δp = change in total pressure.

Δh = change in manometer level on one side of manometer.

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For the inert gas z

$$\text{Initially, moles } z \text{ in gas phase} = \frac{P_z V}{RT}$$

$$\text{moles } z \text{ dissolved} = \frac{V_f \alpha_z P_z}{P_0}$$

$$\text{Total moles } z = P_z \left[\frac{V}{RT} + \frac{V_f \alpha_z}{P_0} \right]$$

$$\text{Finally, moles } z \text{ in gas phase} = \frac{P_z' (V + \Delta v)}{RT}$$

$$\text{moles } z \text{ dissolved} = \frac{V_f \alpha_z P_z'}{P_0}$$

$$\text{Total moles } z = P_z' \left[\frac{V + \Delta v}{RT} + \frac{V_f \alpha_z}{P_0} \right]$$

Since z is inert, total moles z remains constant. Thus, equating, and substituting $\Delta v = M \Delta h$:

$$P_z' = P_z \left[\frac{VP_0 + V_f \alpha_z RT}{VP_0 + V_f \alpha_z RT + P_0 M \Delta h} \right] \tag{1}$$

For the reacting gas x, the same expressions will apply except that now total final moles will be equal to the sum of total initial moles plus males evolved (or absorbed). Thus:

$$P_x' \left[\frac{V + \Delta v}{RT} + \frac{V_f \alpha_x}{P_0} \right] = P_x \left[\frac{V}{RT} + \frac{V_f \alpha_x}{P_0} \right] + x$$

or

$$P_x' = P_x \left[\frac{VP_0 + V_f \alpha_x RT + \dfrac{P_0}{P_x} \cdot RTx}{VP_0 + V_f \alpha_x RT + P_0 M \Delta h} \right] \tag{2}$$

Now to simplify the following operations, let

$$\begin{aligned} VP_0 &= A \\ V_f RT &= B \\ P_0 RT &= C \\ P_0 M &= F \end{aligned} \qquad \begin{aligned} A + B\alpha_x &= X \\ A + B\alpha_z &= Z \end{aligned}$$

Equations (1) and (2) then become:

$$P_z' = P_z \left[\frac{Z}{Z + F \Delta h} \right] \tag{1a}$$

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$$P_x' = P_x\left[\frac{X + \dfrac{Cx}{P_x}}{X + F\Delta h}\right] \tag{2a}$$

Initially: $P_0 = P_x + P_z + P_w$

Finally: $P_0 + \Delta P = P_x' + P_z' + P_w$

$$\Delta P = (P_x' - P_x) + (P_z' - P_z) = 2\Delta h$$

Then from (1a) and (2a):

$$\frac{Cx}{\Delta h} = P_xF + P_zF \cdot \frac{X}{Z} \cdot \frac{\left(1 + \dfrac{F}{X}\Delta h\right)}{\left(1 + \dfrac{F}{Z}\Delta h\right)} + 2(X + F\Delta h)$$

or

$$\frac{x}{\Delta h} = \frac{X}{C}\left[\frac{P_xF}{X} + \frac{P_zF}{Z}\left(\frac{1 + \dfrac{F}{X}\Delta h}{1 + \dfrac{F}{Z}\Delta h}\right) + 2\right] + \frac{2F\Delta h}{C} \tag{3}$$

If, in equation (3), the terms in Δh *on the right* could be neglected, we would be left with a linear equation of the usual form, $x/\Delta h = k$, the entire term on the right becoming the vessel constant. To perform this simplification one must show that the term in Δh within the brackets is essentially equal to unity, and that dropping the final term $2F\ \Delta h/C$ does not introduce an error as great as 1% in the vessel constant. At this point we shall state as a fact that this can be done; the reader is referred to Appendix A for details.

Making these simplifications and substituting the original symbols, we obtain for the vessel constant:

$$k = \underbrace{\left[\frac{\mathbf{V}P_0 + V_f\alpha_xRT}{P_0RT}\right]}_{\textit{Term a}}\underbrace{\left[\frac{P_xP_0\mathbf{M}}{\mathbf{V}P_0 + V_f\alpha_xRT}\right]}_{\textit{Term b}} + \underbrace{\frac{P_zP_0\mathbf{M}}{\mathbf{V}P_0 + V_f\alpha_zRT}}_{\textit{Term c}} + 2\Bigg] \tag{4}$$

It should be observed that the only terms which vary from vessel to vessel are those in boldface, namely **V** and **M**.

C. *Simplified forms of the equation.*

If equation (4) be rewritten in such a way as to separate the major

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terms containing $V_f\alpha$ from those containing V, we obtain a useful form which lends itself to further simplification:

$$k = \frac{2V}{RT} + \frac{V}{RT}\left[\frac{P_xP_0M}{VP_0 + V_f\alpha_xRT} + \frac{P_zP_0M}{VP_0 + V_f\alpha_zRT}\right] + \frac{2V_f\alpha_x}{P_0} + \frac{V_f\alpha_x}{P_0}\left[\frac{P_xP_0M}{VP_0 + V_f\alpha_xRT} + \frac{P_zP_0M}{VP_0 + V_f\alpha_zRT}\right] \quad (4a)$$

In the case of a single gas (e. g. oxygen uptake in an atmosphere of pure oxygen) it will be clear that the terms in z drop out entirely. Furthermore, for any gases of very low solubility (nitrogen, oxygen) the terms $V_f\alpha RT$ become entirely negligible compared with VP_0 and can therefore be neglected. Equation (4a) then reduces to the extremely simple form:

$$k = \frac{2V + M(P_0 - P_w)}{RT} + V_f\alpha_x\left[\frac{2V + M(P_0 - P_w)}{VP_0}\right] \quad (5)$$

The first term in equation (5) is the intrinsic vessel constant (k_0) in the absence of any fluid. Once calculated, it serves as a basis for subsequent transformations to conform to changed conditions. For example, since temperature appears nowhere but in this term, recalculation of constants for changed temperature requires only that k_0 at temperature T_0 be multiplied by the ratio T'/T_0, a procedure which is independent of the gases involved. In the measurement of oxygen uptake (or evolution) the vessel constant is simply k_0 regardless of fluid volume, the solubility being so low that *the entire second term of equation* (5) *becomes negligible.**

Recalculation of constants for different fluid volumes is more involved since every change in V_f is accompanied by an opposite change in V; except for cases (mentioned above) where the second term can be dropped, the entire equation will have to be recalculated.

The principles outlined here are essentially those developed for the constant volume method by Umbreit,[2] (p. 53). Here one must always be certain that the assumptions leading from equation (4a) to equation (5) are valid for the particular experimental conditions obtaining. Of the gases most often measured, *oxygen, as a rule, will yield valid constants by equation* (5); *carbon dioxide usually will require* (because of its high solubility) *that equation* (4) *be used in full.*

* This and similar statements apply, of course, only to usual magnitudes of the various terms in the equations. They are not to be taken in any more general sense but should be re-examined for unusual gas volumes, temperatures, manometer bores, etc.

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For the case of two reacting gases (e. g. oxygen absorbed, carbon dioxide evolved), one can proceed through the same steps as previously, to obtain equation (3) in terms of x and y_z

$$\frac{x}{\Delta h}+\frac{y}{\Delta h}\cdot\frac{X}{Y}\left[\frac{1+\frac{F}{X}\Delta h}{1+\frac{F}{Y}\Delta h}\right]=\frac{X}{C}\left[\frac{P_xF}{X}+\frac{P_yF}{Y}\left[\frac{1+\frac{F}{X}\Delta h}{1+\frac{F}{Y}\Delta h}\right]+\frac{P_zF}{Z}\left[\frac{1+\frac{F}{X}\Delta h}{1+\frac{F}{Z}\Delta h}\right]+2\right]+\frac{2F\Delta h}{C}$$

This is simplified as before, to give:

$$x+\frac{X}{Y}\cdot y=\frac{X}{C}\left[\frac{P_xF}{X}+\frac{P_yF}{Y}+\frac{P_zF}{Z}+2\right]\cdot\Delta h$$

For the special case of R. Q. experiments, let us assume x to be carbon dioxide and y to be oxygen, and the respiration to take place in air. With x absorbed by alkali, y is determined in the usual way:

$$y=k_y\cdot\Delta h$$

Now when *both* gases are reacting, and since the initial $P_x=0$, it can be shown that

$$x=\frac{X}{Y}\left[k_y\cdot\Delta h-y\right]$$

or, substituting symbols, and simplifying the denominator:

$$x=\frac{VP_0+V_f\alpha_xRT}{VP_0}\left[k_y\cdot\Delta h-y\right] \qquad (6)$$

It is clear from equation (6) that the constants for carbon dioxide are not required, x being obtained indirectly from k_y and the known evolution of y, separately determined.

D. *The thermobarometric correction.*

In the constant volume method the effects of temperature variation and changes in atmospheric pressure are reflected in an equal change in the level of all manometers, regardless of gas space, fluid volume, temperature, or the particular gases present. In the free manometer

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method this is not strictly true, although it will usually be possible to consider it so without significant error.

It can be shown (see Appendix B) that for a temperature change ΔT,

$$\Delta h = \frac{1}{T\left(\frac{2V + P_0M}{VP_0}\right)} \cdot \Delta T$$

If we make the reasonable assumption that the temperature variation will never exceed 0.2°, the *total* Δh due to ΔT will be about 2.5 mm., and the *differences* between several vessel-manometer combinations will be entire negligible.

Unfortunately, the changes of level due to small variations in atmospheric pressure cannot always be disposed of so simply. It can be shown (see Appendix B) that for a change in atmospheric pressure ΔP_0,

$$\Delta h = \frac{V}{2V + P_0M} \cdot \Delta P_0$$

Here differences between vessels become significant (> 0.5 mm.) when $\Delta P_0 > 10$ (or about 0.8 mm. mercury). It should be noted, however, that as compared with the constant volume method, the actual Δh due to ΔP_0 is exceedingly small.

In experiments of several hours duration we have found it unusual for the thermobarometer to vary more than 5 mm. (a variation which corresponds to about 15 mm. in the constant volume method). Should this figure not be exceeded, the thermobarometric correction may be treated in the customary way without detectable error. For greater variations a correction term may be introduced:

$$\Delta h_x = \left[\frac{\frac{2V_1 + P_0M_1}{V_1}}{\frac{2V_x + P_0M_x}{V_x}}\right] \cdot \Delta h_1 \qquad (7)$$

where Δh_1 is the change in level of the thermobarometer, and Δh_x is the appropriate correction to be applied to any particular vessel. It should be noted that the terms which appear in this correction factor must all have been calculated previously in determining the constant for each vessel. Use of this thermobarometric correction factor, which is independent of temperature, fluid volume, or the nature of the gases present, permits accurate readings despite large changes in atmospheric pressure.

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It will be observed from the above equations that the magnitude of manometer excursion due to thermobarometric changes, and consequently of differences in manometer responses, can be minimized by employing a small vessel with a manometer of large bore. The smaller vessel also increases the general sensitivity of the method, thus curiously *increasing* the manometer excursion in response to gas changes while at the same time *decreasing* its excursion in response to thermobarometric changes. A large manometer bore, on the other hand, markedly *decreases* the general sensitivity of the method, while very large bores (of the order of 2 mm.) introduce errors into the method. The practical expedient, therefore, is to use, if possible, *small vessels with small-bore manometers;* to choose such combinations of vessels and manometers as will tend to equalize the $M : V$ ratios; and to select as thermobarometer that combination having an intermediate $M : V$ ratio.

Unlike customary procedure, the thermobarometer here should contain approximately the same amount of fluid as the other vessels, and should be calibrated for V and M.

Application of the Method

A. *Practical procedures.*

We have shown that from a theoretical standpoint, within an error of 1%, the free manometer method will give readings which are proportional to the amount of gas liberated or absorbed. The vessel constant can be calculated (as illustrated in the next section) from the same data required in the constant volume method, once the *linear volume* of the manometer has been determined to an accuracy of about 1%. Or the vessel constant can be found empirically by measuring the release of a known amount of gas.

No special apparatus is required. Small vessels (about 10 cc.) are preferable to large. Manometers of small bore (about 1 mm.) are also preferred. If the inside diameter is greater than 1.5 mm. significant errors may be introduced. The bore of a set of manometers ought not to vary widely. Precautions should be taken to prevent fluid being inadvertently added or removed during the progress of a reaction.

Small thermobarometric changes (5 mm. or less) may be treated in the customary way. Whether large changes will be reflected equally in all vessels depends entirely upon the $M : V$ ratios for the various vessel-manometer combinations. Inspection of equation (7) will reveal the significance of the differences for any particular set of vessels and manometers. Thermobarometric changes exceeding 5 mm. in a period of several hours are rarely encountered in practice.

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For *oxygen uptake*, with carbon dioxide absorbed, the simplest form of the vessel constant equation applies (equation (5) without the second term).

For *R. Q. determinations*, the carbon dioxide constant is not needed. Using the oxygen constant alone, the evolved CO_2 is determined from the oxygen uptake with CO_2 absorbed, and the *apparent* oxygen uptake with both gases present. (See equation (6).)

For CO_2 *evolution*, because of the high solubility, it is necessary to use the full equation (4). The simplified form, equation (5), gives constants that are too large by about 2%.

Ordinarily readings are started by closing the stopcocks and simply setting the fluid *in the vessel arm* of each manometer to 150. The manometers are then not touched again, and calculations are much simplified by the fact that all subsequent readings are substracted from 150. If, despite the increased capacity of the free manometer technique, it becomes necessary to reset the manometers, this can be done very simply. The stopcocks are opened momentarily to allow fluid to equalize in both manometer arms. It is immaterial whether this level is exactly 150 or (because drainage is incomplete) somewhat lower. The reading at the moment of resetting is called 150 and, provided drainage is complete by the time of the next reading, no error is introduced.

If a very large gas evolution or uptake is to be measured, the capacity can be doubled by setting to 150 with the stopcocks open, applying positive pressure to the appropriate arm of the manometers, and closing the stopcocks while fluid is thus displaced almost entirely into one manometer arm. The zero time reading will then be close to 300, or to 0, as the case may be, and the entire length of the manometer will be available for subsequent fluid excursion.

B. *Typical determination of a vessel constant.*

Vessel no. 2. Manometer no. 2.

Weight of mercury filling vessel to neck mark of manometer at 26°: 234.5 Gms. Calculated volume to neck mark: 17.33 cc. In this step the weighing need be done to no better than 0.1 Gm. Now filling the manometer with mercury from the neck mark to a point above and then below the 150 mark, we find:

Neck mark to 80.5 (23°) : 10.27 Gms. mercury.

Neck mark to 173.0 (23°) : 8.35 Gms. mercury.

Then 92.5 mm. mercury at 23° weighs 1.92 Gms. and $M = 1.54$ cu. mm. per mm.

Neck mark to 150 (by interpolation) : 0.65 cc.

Note that the weighings in this section must be to 0.01 Gm.

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As a check on the above value of M, and in order to ascertain the constancy of the manometer bore, we ran a bit of mercury 50 to 200 mm. long into the manometer. By measuring its length at different portions of the manometer we could verify the uniformity of the bore; the length of the column never changed by more than 1 mm. and no systematic narrowing or widening of bore was ever noted. Thus:

189 mm. mercury at 23° weighed 3.92 Gms.
109 mm. mercury at 23° weighed 2.28 Gms.
From which $M = 1.54$.

It should be clear from the above data that an error in excess of 1–2% in M could not reasonably occur. It is demonstrated in Appendix C that for a manometer of this bore, an error of up to 4% would be quite tolerable.

The vessel constant for CO_2, for a fluid volume of 2.2 cc. and a temperature of 27° C. is calculated as follows, using equation (4)

Total volume to 150 mark: 17,980
V_f: 2,200
V: 15,780
M: 1.54
T: 300
P_0: 1.004×10^4 mm. manometer fluid (of density 1.030).
Gas mixture: 95% N_2 — 5% CO_2
P_w: 26.74 mm. mercury at 27° = 353 mm. manometer fluid.
P_{CO_2}: 484.
P_{N_2}: 9198.
R: 8.21×10^8
α_{CO_2}: 3.20×10^{-8} moles per cu. mm.
α_{N_2}: 6.22×10^{-10}

In the following, the lettered terms refer to equation (4), which is used in full.

VP_0	1.586×10^8
$V_f RT\alpha_{CO_2}$	0.174×10^8
$VP_0 + V_f RT\alpha_{CO_2}$	1.760×10^8
$P_0 RT$	0.248×10^{16}
Term (a)	7.09×10^{-8}
$P_{CO_2}\ P_0 M$	7.45×10^6
Term (b)	0.04
$P_{N_2} P_0 M$	1.416×10^8
$V_f RT\alpha_{N_2}$	0.003×10^8
$VP_0 + V_f RT\alpha_{N_2}$	1.589×10^8
Term (c)	0.89

(b) + (c) + 2 = 2.93
2.93 × (a) × 10^6 = 0.208 μM per mm. = k.

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C. *Experimental confirmation of the method.*

The validity of the free manometer method was confirmed by direct quantitative recovery of weighed bicarbonate, and by simultaneous determinations of enzymatically-controlled acid production in bicarbonate medium (plasma cholinesterase plus acetylcholine), and of oxygen uptake by a bacterial suspension. Vessel volumes varied from 16.22 to 20.29 cc. and manometer bores from 1.37 to 1.99 mm. diameter (M from 1.48 to 3.12). Fluid volumes of 2.2 and 5.5 cc. were employed.

In all such replicate determinations the free manometer and constant volume methods were in satisfactory agreement. The actual data obtained in one such confirmatory experiment are presented in Table 1, which readily allows comparison of the capacity and sensitivity of the two methods.

Appendix A. *The simplification of equation* (3).

It will be recalled that the elimination from equation (3) of certain terms in Δh was a prime necessity in transforming a complex function to a linear equation which would yield an expression for the vessel constant. The justification for this transformation will now be presented. In the following, a change which introduces a net error of less than 1% into the vessel constant will be accepted. Where Δh appears it will be assigned its maximum possible value, 150, to bring out the greatest errors that may arise through the simplifications.

The manipulations performed on equation (3) involved the dropping of the terms in Δh from two places. First we shall consider the elimination of the term

$$\left(\frac{1 + \frac{F}{X} \Delta h}{1 + \frac{F}{Z} \Delta h} \right)$$

from within the brackets. Substituting the proper symbols makes it apparent that the resulting fraction

$$\left(\frac{1 + \frac{P_0 M}{V P_0 + V_f \alpha_x R T} \Delta h}{1 + \frac{P_0 M}{V P_0 + V_f \alpha_z R T} \Delta h} \right)$$

must practically equal unity unless α_x and α_z differ considerably from each other. For oxygen and nitrogen, for example, both solubilities

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TABLE 1

Enzymatic hydrolysis of 17.7 μM acetylcholine bromide by cholinesterase, *simultaneously* determined by both methods. The first two columns under each method give actual readings in mm. The third columns give computed μM CO_2.

	Free Manometer			Constant Volume		
Vessel:	9	10	μM CO_2	12A	7	μM CO_2
Constant:	0.274	TB		TB	0.0640	
	Set at	Set at				
18′	150	150	0	148.5	169	0
20′	140.5	150.5	2.74	148.	210.	2.68
22′	132.	151.	5.20	147.5	246.	4.99
24′	124.	151.	7.40	148.	281.5	7.23
26′	114.	148.	9.32	158.	120.*	9.20†
28′	107.5	147.5	10.96	159.	148.	10.93
30′	102.5	148.	12.47	158.5	171.5	12.46
32′	98.	148.5	13.83	158.	191.	13.74
34′	94.5	148.5	14.80	157.	207.5	14.86
36′	92.	149.	15.62	156.	220.5	15.76
38′	90.	149.5	16.30	155.	229.	16.36
40′	89.	150.	16.70	154.	234.	16.75
Total Δh	61.0 mm.			226.5 mm.		
Extreme TB variation	3.5 mm.			11.5 mm.		
1 μM equals	3.7 mm.			15.6 mm.		
1 mm. equals	0.274 μM			0.0640 μM		

* Re-set manometer here. † Extrapolated value.

are so small and so similar that by no reasonable combination of other terms could the entire fraction be made as great as 1.01 or as small as 0.99. Thus the error could not exceed 1% even if this were the only term in the equation. As a matter of fact, the term under consideration is added to two others in equation (3) so that we are allowed an error in excess of 1% for the term itself. When the two gases are carbon dioxide and nitrogen, whose solubilities differ so greatly, one can no longer categorically dispose of the term as negligible. However

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if we confine ourselves to reasonable magnitudes for the various terms it can still be shown that the one under consideration cannot exceed the limits indicated. For example, if $V > 5000$, $V_f = 2200$ (or 5500 when V is as large as 15,000), T about 300, the term is still between 0.99 and 1.00, provided M is less than 2. At larger total gas volumes M may be as large as 3 but when the actual manometer volume becomes a significant fraction of the total volume, the linearity of the equation no longer holds.

The same arguments apply to the elimination of the similar term in X and Y from the equation for two reacting gases and one inert gas.

The validity of dropping the final term $\frac{2F\,\Delta h}{C}$ depends primarily upon M. Substituting for the symbols, $\frac{2P_0M\,\Delta h}{P_0RT} = \frac{300M}{RT}$ for maximum Δh. R being constant, and T being subject to small differences (relative to its own magnitude), the numerical value becomes, approximately, $M \times 0.001 \times 10^{-6}$. Since the smallest value of the vessel constant may be of the order of 0.200×10^{-6} it follows that the error due to dropping this term may vary from 0.5% when $M = 1$, to 1.5% when $M = 3$. Both errors refer to extreme readings of the manometer; for readings below 150 the errors will, of course, be correspondingly smaller.

In summary, the two terms can be dropped without introducing a significant error. At full gas evolution (or absorption) the error just exceeds 1% if the manometer factor is as large as 3. It will now be understood why a large bore manometer is inadvisable. The equations will be most valid (i. e., reactions will run truly linearly) for small M, and a value between 1 and 1.5 should prove practical. This corresponds to a bore *diameter* between 1.1 and 1.4 mm., a range into which, fortunately, most manometers of recent make fall.

APPENDIX B. *Derivation of the thermobarometric correction.*

For change in T:

Initially $pv = NRT$

After ΔT, $\qquad (p + \Delta p)\,(v + \Delta v) = NR\,(T + \Delta T)$

Expanding, and dropping $\Delta p\,\Delta v$, $\Delta v = \frac{NR\Delta T - V\Delta p}{p}$

Substituting $\Delta v = M\Delta h$, $\Delta p = 2\,\Delta h$, and $p = P_0$

$$\Delta h = \frac{NR\Delta T}{P_0M + 2V}$$

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But

$$NR = \frac{P_0 V}{T}$$

Thus

$$\Delta h = \frac{P_0 V}{T\,(2V + P_0 M)} \cdot \Delta T$$

For change in P_0:

Initially, inside vessel $pv = NRT$

After ΔP_0, $(p + \Delta p)\,(V + \Delta V) = NRT$

Expanding, subtracting, and dropping $\Delta p\,\Delta v$:

$$\Delta p = \frac{P_0}{V} \cdot \Delta V$$

Now the change in atmospheric pressure will equal the sum of the pressure change within the vessel and the pressure change shown on the manometer; or, $\Delta P_0 = \Delta p + 2\Delta h$. Substituting as above:

$$\Delta h = \frac{V}{2V + P_0 M} \cdot \Delta P_0$$

Net thermobarometer change:

$$(\Delta h)_{TOTAL} = \frac{P_0 V}{T\,(2V + P_0 M)} \cdot \Delta T + \frac{V}{2V + P_0 M} \cdot \Delta P_0$$

$$= \frac{V}{2V + P_0 M}\left[\frac{P_0}{T} \cdot \Delta T + \Delta P_0\right]$$

and since the term in the brackets applies equally to *all* manometers and vessels,

$$\Delta h_x = \left[\frac{\dfrac{2V_1 + P_0 M_1}{V_1}}{\dfrac{2V_x + P_0 M_x}{V_x}}\right] \cdot \Delta h_1$$

APPENDIX C. *The determination of M.*

To what accuracy must M be determined, and is the required accuracy obtainable by the usual calibration procedures? It is simplest to examine the question first from the standpoint of equation (5), although the same considerations apply to the full equation (4).

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M only appears in the term $2V + M(P_0 - P_w)$ where any error will be reflected as an error of the same degree in the whole vessel constant. The problem is therefore to determine M so accurately that the error, ΔM, will be less than 1% of the entire expression in which M appears:

$$\Delta M < 0.01 [2V + M(P_0 - P_w)]$$

For $V = 1 \times 10^4$, $\Delta M < 0.03$ when $M = 1$; $\Delta M < 0.04$ when $M = 2$; and $\Delta M < 0.05$ when $M = 3$. The assumed value of V is a reasonable one; if V is larger the permissible error in M may be greater, and conversely. The required accuracy of determining M is given by $\Delta M/M$, which is 3%, 2%, and 1.7% respectively, when M equals 1, 2 and 3, at the assumed value of V.

We were concerned with the practical question whether a small-bore manometer could be calibrated with sufficient accuracy. A manometer of approximate bore 0.7 mm. was filled with columns of mercury 25 to 150 mm. long, the mercury weighed, and the operation repeated four times. The results were as follows (22°):

133.0 mm.	0.712 Gms.	0.00536 Gms. per mm.
25.0	0.134	0.00536
150.5	0.805	0.00535
151.0	0.811	0.00537

$M = 0.396$ Maximum error = 0.75%

In the case $M = 0.4$, the permissible error is 7% so that the accuracy obtainable is nearly ten-fold that required. The calibration of a manometer of larger bore having been demonstrated earlier, it is evident that the actual determination of M presents no practical difficulty.

Summary

1. A "free manometer" technique for use with the standard Warburg apparatus has been described, wherein the manometer fluid is not levelled. Although, as a consequence, both pressure and volume vary, the change in fluid level remains (within acceptable limits of error) a linear function of the quantity of gas evolved or absorbed.

2. The method opens the way to automatic recording of the progress of reactions. It also substantially increases the amount of evolved or absorbed gas that can be measured by a standard manometer.

3. The method has been derived in general theoretical terms, its practical application discussed, and its validity confirmed experimentally.

I am indebted to Dr. Paul Olum for helpful advice in connection with the mathematical treatment, and to my wife for suggestions and experiments bearing on the practical use of the method.

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AN EXPERIMENTAL STUDY OF THE ABSOLUTE TEMPERATURE SCALE

X. Comparison of the scale of the platinum resistance thermometer with the scale of the nitrogen gas thermometer from 0° to 444.6° C: reduction of the observations

By James A. Beattie, Manson Benedict,
B. Edwin Blaisdell, and Joseph Kaye

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(Contribution from the Department of Chemistry,
Massachusetts Institute of Technology, Cambridge, Massachusetts)

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1. INTRODUCTION

The primary instrument for the determination of temperatures on the thermodynamic scale is the gas thermometer. But the complexity of the equipment and the labor of correcting the observations for the lack of ideality of the apparatus and of the thermometric fluid led to the search for an instrument requiring less computation for conversion of the measured property into temperature and one that is convenient in form, reproducible in its indications, and useful over a wide range of temperatures. Callendar [1] showed that the resistance of a platinum wire is a suitable property for the definition of a temperature scale. His design of a support for the platinum resistor, procedures for calibration, and formula for converting resistance into temperature are essentially those in use today.

The Callendar equation (see Table III) expresses the resistance of a platinum wire as a quadratic function of the thermodynamic Centigrade temperature. Three fixed points whose thermodynamic temperatures

[1] H. L. Callendar, Phil. Trans. Roy. Soc. London, *178A*, 160-239 (1887).

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are known must be used to determine the three constants (R_0, α, and δ) of the formula. It is desirable though not necessary that two of these be the fixed points that determine the size of the Centigrade degree: the ice point (0° C.) and the steam point (100° C.). Callendar proposed the sulphur boiling point for the third.

Before the indications of a secondary instrument, as the platinum resistance thermometer, can be accepted with confidence for the realization of the thermodynamic temperature scale, it is necessary to determine: (1) the reproducibility of the temperature scale of a single instrument; (2) the agreement of the scale of one such instrument with that of another; (3) the thermodynamic temperatures of the calibration points; and (4) the agreement of the scale of the thermometer with the thermodynamic scale at temperatures removed from the calibration points.

The first two of the above questions will be considered in a later publication. However, it might be mentioned that the present investigation shows that four platinum resistance thermometers, recently calibrated, indicate the same temperature in the range 0° to 450° C. with a maximum spread of about 0.001° C. As regards the last two questions we are concerned here with the temperature range 0° to 450° C.

Callendar believed that his equation would give temperatures on the thermodynamic Centigrade scale to 1° C. from 0° to 500° C. Certainly the deviations are much smaller than this. But how much smaller and even the sign of the deviation has not been settled. In 1941 Mueller[2] wrote ". . . gas thermometry in the range 0° to 660° C. is not yet sufficiently precise to determine that the formula is inadequate."

Comparisons of the indications of the platinum resistance thermometer with those of gas thermometers above 0° C. have proceeded along three lines.

1. In the range 0° to 100° C. temperatures measured on the platinum resistance scale have been compared with those indicated by standard mercury thermometers which in turn had been calibrated against a standard hydrogen gas thermometer through the investigations of Chappuis.[3] The deviations of the platinum resistance from the gas scale found by Chappuis and Harker[4] did not show any definite trend with temperature and seem to be within the accuracy (0.02° C.) of the

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[2]F. F. Mueller, *Temperature*, pp. 162-179. Reinhold Publishing Company, New York (1941).

[3]P. Chappuis, Trav. et Mém. Bureau Int., *6*, 125 + 187 pp. (1888); ibid., *13*, 66 pp. (1907).

[4]P. Chappuis and J. A. Harker, Trav. et Mém. Bureau Int., *12*, 90 pp. (1902); Phil. Trans. Roy. Soc. London, *194A*, 37-134 (1900); P. Chappuis, Phil. Mag., (6) *3*, 243-247 (1902).

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mercury thermometers of that time; those found by Dickinson and Mueller[5] and by Hall[6] did not exceed 0.003° C. and were within the accuracy of the mercury thermometers.

2. Above 100° C. and up to 1100° C. the platinum scale has been compared with the gas scale through the measurement of the temperatures of certain fixed points, as the freezing points of tin, zinc, antimony, copper, silver, and gold, the boiling points of naphthalene, benzophenone, etc. These points as well as the sulphur boiling point have been determined[4,7-15] a number of times on the thermodynamic scale by the use of gas thermometers, usually with nitrogen as the thermometric substance. Comparison of the platinum resistance thermometer scale with that of the gas thermometer through the intermediary of fixed points were made by Waidner and Burgess,[16] Adams and Johnston,[17] and Moser.[18] Waidner and Burgess concluded that the platinum resistance scale agreed with the gas scale from 0° to 1100° almost within the reproducibility of the latter; but Adams and Johnston, and Moser found that a third term should be added to the Callendar formula for the higher temperatures. Moser adds to the right-hand side of the Callendar equation (see Table III) the term with γ having the values + 0.0027, +

$$\gamma \frac{t}{100}\left(\frac{t}{100}-1\right)\left(\frac{t}{444.6}-1\right)$$

[5]H. C. Dickinson and E. F. Mueller, Bull. Bureau Standards, *3*, 641-661 (1907).

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[15]P. Chappuis, Trav. et Mém. Bureau Int., *16*, 44 pp. (1917).

[16]C. W. Waidner and G. K. Burgess, Bull. Bureau Standards, *6*, 149-230 (1909-10); ibid., *7*, 1-9 (1911).

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0.0042, and + 0.0053 for the three thermometers used by him. The value of γ was determined by use of a fourth calibration point: the melting point of gold, 1063° C.

3. Direct comparison of platinum resistance thermometers against gas thermometers have been made by a number of investigators. Chappuis and Harker[4] compared the two scales to about 600° C. and Harker[19] compared them to 1000° C. both using nitrogen gas thermometers. Harker concluded that "the divergence of the two scales only exceed the probable error at the higher part of the range." Holborn[20] and Holborn and Henning[21] compared the platinum scale against those of the nitrogen, hydrogen, and helium gas thermometers from 150° to 450° C. The average differences at each temperature do not exceed 0.01° C. and the uncertainty in the gas thermometry was placed at 0.02° C., a rather optimistic estimate. Dickinson and Mueller[22] compared platinum resistance thermometers against the nitrogen gas thermometer of Day and Sosman[14] at 306°, 445°, and 630°. Henning and Hense[23] compared platinum resistance thermometers against a helium gas thermometer finding the difference t(gas) - t(platinum) to be + 0.007° at 20° - 0.005° at 50° and + 0.004° at 80° C.

The result of the vast amount of work done on the scale of the platinum resistance thermometer can be summed up in the statement that to at least 450° C. the Callendar formula is much better than 1°, possibly as good as 0.1° C. But the actual deviations of the platinum scale from the thermodynamic scale are not known nor is the sign of the deviations well established.

In 1927 the Seventh General Conference of Weights and Measures adopted[24] an International Temperature Scale which in the range 0° to 660° C is based on the indications of a standard platinum resistance thermometer calibrated at the ice, steam, and sulphur boiling points (to which the value 444.6° C. was assigned), and used in conjunction with the Callendar formula. It was stated that the "Thermodynamic Centigrade Scale . . . is recognized as the fundamental scale to which all temperature measurements should ultimately be referable"; and that the International Temperature Scale "conforms with the thermodynamic scale as closely as possible with present knowledge." Cer-

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tain details of construction of a standard platinum resistance thermometer are specified, and the purity and physical condition of the platinum are controlled by the specification that the ratio of resistances R_t/R_0 shall be not less than 1.390 for $t = 100°$ C. and not less than 2.645 for $t = 444.6°$ C.

We have constructed[25] standard platinum resistance thermometers for the realization of the International Temperature Scale and studied their calibration at the ice point,[26] steam point,[27] and sulphur boiling point.[28] The reproducibility of these fixed points and the effect of pressure on the boiling points were investigated and a method of making the boiling points independent of the atmospheric pressure proposed. The boiling point of mercury[29] was also investigated as a possible fixed point in thermometry.

In earlier publications we have described[30] a duplicate nitrogen gas thermometer for realization of the thermodynamic temperature scale in the range 0° to 450° C. and derived[31] equations for correction of the observations for the imperfection of the apparatus and of the thermometric fluid. During the course of the study of the temperature scale, determinations[32] of the thermal expansion and compressibility of vitreous silica and of the thermal dilation of mercury were made, and three methods[33] of determining the capillary constant of mercury in a manometer were investigated in order that the capillary depressions and meniscus volumes of mercury may be computed from Blaisdell's[34] tables.

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2. COURSE OF THE PRESENT INVESTIGATION

A total of 394 comparisons of temperatures on the International Temperature Scale as realized by four standard platinum resistance thermometers were made with temperatures on the thermodynamic scale as determined from the indications of two nitrogen gas thermometers, designated Red and Green. The first 110 runs were preliminary in nature and were designed to study the performance of the equipment. During these runs various changes in apparatus, procedure, and methods of calibration were made. The results of the final measurements, Runs 111 to 394, are given in Table XI.

A detailed description of the apparatus has been given[30] together with calibration methods, tests for defects, performance of the various components, determination of purity of the nitrogen, and procedure for a run.

TABLE A
Scheme of the Runs

Approximate ice point pressure stand. mm. Hg.	Run Nos.	Nominal run temperature, °C. Int.											
		0	25	50	75	100	150	200	250	300	365.58[a]	400	444.6[b]	Total
		Number of runs made at each temperature												
1. Runs Made in the Oil Thermostat														
1000	111-135	11	2	2	2	8								25
750	136-167	14	2	2	2	10	2							32
450	168-199	14	2	2	2	8	4							32
600	200-225	12				8	6							26
333	226-251	12				8	6							26
2. Runs Made in the Nitrate Thermostat														
333	252-308						28	3	3	3	5	3	12	57
600	309-356						26	2	2	2	4	2	10	48
450	357-394						18	2	2	2	4	2	8	38

[a]Normal mercury boiling point.
[b]Normal sulphur boiling point.

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The scheme of the runs is given in Table A. All observations were reduced in the same manner and from the same calibrations and properties of materials with one exception: after Run 379 the vacuum over the long arms of the main manometer was accidently broken and the mercury in the long arm was visibly fouled. Hence for Runs 380 through 394 we used the capillary constant $a = 2.48$ cm. for the mercury in the long arms as determined[30] after the completion of Run 394; we continued to use $a = 2.66$ for the mercury in the short arms.

3. IDENTIFICATION OF THE THERMOMETER SPACES

The following brief discussion is given to identify the various parts of the thermometer system; detailed descriptions have been given elsewhere.[30, 31] In Figure 1 is given a sketch showing the main thermometer system AS and the auxiliary thermometer system A_aS_a for one of our gas thermometers. The main thermometer system from A to E and the auxiliary thermometer system from A_a to E_a were enclosed in steel cases to which the same external pressure p_e of nitrogen was applied. Convection currents were eliminated in the region of large thermal gradient by plugs of asbestos cord.

The parts of the main thermometer system are as follows:

1. The vitreous silica Bulb b extended from A to C and included a small volume consisting of the graded seal from vitreous silica to pyrex glass.

2. The Dead Space 1 extended from C to D. It was of pyrex and included the region of large thermal gradient. The calculation of the exact length of capillary to be associated with the auxiliary thermometer was given in an earlier paper.[31]

3. The Dead Space 2, of stainless steel, extended from D to E.

4. The Dead Space 3 extended from F to H. The capillaries were of stainless steel and the valve FG was of ordinary steel. The point H was clamped to a steel rod screwed into the steel top of the thermostat vessel. The vertical distance from H to the index mark in the short arm of the main thermometer was measured for each thermostat temperature.

5. The Dead Space 4, a stainless steel capillary, extended from H to I. At I the capillary entered the air thermostat around the main manometer tubes.

6. The Dead Space 5 extended from I to the mercury surface S in the lower manometer tube.

The parts of the auxiliary thermometer system are:

1. The Bulb A_aD_a of pyrex glass.

2. The Dead Space D_aS_a, consisting in part of a stainless steel capillary and in part of pyrex glass.

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4. REDUCTION OF THE OBSERVATIONS

The average of the values of the six observations that constituted a run[30] were combined to give the quantities measured in each run listed in Table I.

The vertical distance H from the crown of the mercury meniscus in the short arm of the main manometer to the crown in the long arm, the the heights h_1 and h_2 of the mercury menisci in the long and short arms, respectively, and the vertical distance h_3 from the crown of the meniscus to the index point in the short arm are given by the relations:

$$\begin{aligned} H &= D_1 - D_2 + m\,(M_1 - M_2 - S_1 + S_2), \\ h_1 &= m\,(M_1 - N_1), \\ h_2 &= m\,(M_2 - N_2), \\ h_3 &= m\,(P_2 - M_2), \end{aligned} \tag{1}$$

where:

M_1 [M_2] = average reading of the micrometer head of the upper [lower] telescope when the cross-hair of the ocular was set on the crown of the mercury meniscus in the long [short] arm of the manometer.

N_1 [N_2] = average reading on bottom of the meniscus.

P_2 = average reading on the index point in the short arm.

S_1 [S_2] = average reading on scale division D_1 [D_2].

D_1 [D_2] = scale division nearest cross-hair of upper [lower] telescope when set on M_1 [M_2]

m = number of units on the scale for one complete turn of the micrometer head, same for both telescopes.

The pressures in the auxiliary thermometer system and in the metal cases surrounding the thermometer bulbs were determined from the vertical heights H_a of the mercury column in the auxiliary manometer, and H_B in a barometer. Each height was determined to 0.1 mm. of mercury or better. The long arm of the auxiliary manometer was evacuated, but one end of the external manometer was open to the atmosphere.

The temperatures t_s, t_2, t_3, t_4, t_{Hga}, t_{da}, t_e of the scale, the Dead Spaces 2, 3, 4, the mercury in the auxiliary manometer, the dead space of the auxiliary thermometer, and the room, respectively, were measured by calibrated mercury thermometers that could be read to 0.01° C. The average temperature t_{Hg} of the mercury in the main manometer was computed from the indications of five standard platinum resistance thermometers enclosed in the manometer housing, the lowest thermometer reading the temperature t_5 of the Dead Space 5. The temperature t_b of the bulb of the main thermometer was the average of the indications of four standard platinum resistance thermometers. All indications of the gas thermometer were corrected to one of the nominal temperatures shown in Table A.

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In Table II are given the calibration quantities and properties of materials used in reducing the observations on the gas thermometers. These are employed in the relations of Tables IV to X.

Table III gives the Callendar equation for converting the measured resistance R_t of a platinum resistance thermometer into temperature when R_0 α and δ are known. Since the equation is implicit in t, a provisional value of t is first computed with an estimated value substituted into the last term of the expression, and then a second approximation made with the aid of the provisional value. Usually no further calculation is required to find t to 10^{-6} °C. In order to set the thermostat temperature at any desired value, we can compute the corresponding resistance from the relation:

$$R_t = R_0 \left\{ 1 + \alpha \left[t - \delta \left(\frac{t}{100} \right) \left(\frac{t}{100} - 1 \right) \right] \right\}$$

In Table III are also given the relations for computing the values of α and δ from calibration measurements and the equations found in earlier investigations[26,27,28,29] for the effect of pressure on the various equilibrium temperatures. In the main body of Table III are given the measured values of α and δ for the platinum resistance thermometers used to measure the temperature t_b of the bulbs of the gas thermometers on the International Temperature Scale. The resulting values of t_b are listed in Columns 3, 4, and 5 of Table XI. Table III also gives a list of the runs in which each thermometer was used, and the dates of calibration of the thermometer bridge. The bridge corrections were considered to vary linearly with time between calibration dates, and to be constant during each calendar month and have the value computed for the middle of the month.

In the reduction of the gas thermometer observations the pressure p' in standard millimeters of mercury at the mercury surface in the short arm of the manometer was computed from the height H of the mercury column by the relation:

$$p' = (H + \delta_1 - \delta_2 + \delta_3) F, \qquad (2)$$

where:

δ_1 = capillary depression (mm.) of mercury in the long arm of the manometer.

δ_2 = capillary depression (mm.) in the short arm.

δ_3 = correction (mm.) for ruling error of the scale, its thermal expansion and stretch, and the compressibility of mercury.

F = factor for reducing mercury heights to 0° C. and standard gravity.

The correct pressure p at the nominal temperature t_r that would have been observed if the gas thermometer had been an idealized instrument[31] is:

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$$p = p' + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8 \qquad (3)$$

where:

δ_4 = gravitational correction (standard mm. of mercury).

δ_5 = correction (standard mm. of mercury) for variation in volume of the system on the assumption that the thermometric gas is ideal.

δ_6 = correction (standard mm. of mercury) for variation in temperature of the system on the assumption that the gas is ideal.

δ_7 = correction (standard mm. of mercury) to $\delta_5 + \delta_6$ for the imperfection of the gas.

δ_8 = correction (standard mm. of mercury) to the nominal temperature of the run.

Values of δ_1, δ_2, δ_3, and F are listed in Table IV. The corrections δ_1 and δ_2 depend on the capillary constant a of mercury, the height h of the meniscus and the bore d of the manometer tubes, the latter being constant for each short arm and a function of H for the long arms. The diameters of the manometer tubes are listed in Table II-3. The capillary depression of mercury as a function of h and d are given for $a = 2.66$ and $a = 2.48$ in Table II-2(b). From these tables the values of δ_1 and δ_2 listed in Table IV were derived. The correction δ_3 depends for a given equipment on the height H of the mercury column and the temperature t_s of the scale. The data for evaluating the coefficients of the terms of δ_3 are given in Tables II-1 and II-2(a). Data for computing the factor F, which depends on the temperature t_{Hg} of the mercury column and on local gravity, are given in Tables II-2(a) and II-1(b).

The outline of the computation of the value of the reciprocal temperature averaged with respect to the area of the capillary CD, Fig. 1, for the region of large thermal gradient is given in Table V. This quantity is $1/T_1$ for the Dead Space 1. The theory of the use of an auxiliary thermometer for evaluating $1/T_1$ was developed in an earlier paper[3 1]. The value of $1/T_1$ is listed in Table XI for each run, but the details of the calculation for each run are not given. For every run we measured H_a, t_{Hga}, and t_{da} for each of the two auxiliary thermometer systems, one for each main thermometer. From these and the calibration function ϕ_{an} it is possible to compute $1/T_1$ from the equations given in Table V.

The equations and tables for computing the gravitational correction δ_4 are given in Table VI. The correction consists of a sum of terms, one for each thermometer space, and depends on the ratio of the vertical height l of the column of gas to the average Kelvin temperature T of the space. The length of each thermometer space (except l_4) at 27° C. and its variation with temperature are given in Table II-5. In Table VI are given: the ratio $l/_bT_b$ for the bulb space at each nominal

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temperature of a run; the length l_4 for each nominal temperature; l_1 as a function of $1/T_1$; and l_2, l_3, and l_5, which did not vary by as much as 0.05 mm. during the course of the investigation. Each height was rounded off to the nearest 0.1 mm. at each temperature. Since the actual temperature of a run was within 0.01° C. of the nominal temperature with only a few exceptions, the values of l_b/T_b and l_4 for the nominal temperature were used for all runs at a given temperature. To l_5 must be added the distance h_3 from the index mark to the crown of the mercury meniscus in the short arm of the manometer. The reciprocal temperature $1/T_1$ was obtained directly from the auxiliary thermometer, while T_b, T_2, T_3, T_4, and T_5 were computed from the corresponding centigrade temperatures on the International Scale and the corrections listed in Table II-7.

The equations and tables for correction δ_5 are given in Table VII. This correction is combined with δ_6 for the Dead Space 1[31]. The volumes of the various thermometer spaces, their coefficients of thermal dilation and the compressibility and dilation with difference between internal and external pressure of the main thermometer bulbs are given in Table II-4. In Table VII are listed values permitting quick computation of the volume $V(t_b, p', p_e)$ of the thermometer bulb at any temperature t_b near a nominal temperature t_r, internal pressure p', and external pressure p_e. The error introduced by the use of p' as the pressure at the center of the bulb instead of p'plus the pressure of the column of gas from the mercury surface to the center of the bulb is considered later. The variation of the volumes of the Dead Spaces 2 to 5 with temperature are also given in Table VII. The volume V_5 is a function of h_3 and of h_2. The covolume of the mercury meniscus depends on the capillary constant a of the mercury, the radius d_2 of the tube, and the height h_2 of the meniscus. The tube diameters are listed in Table II-3, and values of the ratio of the covolume of a mercury meniscus to the volume of an equivalent cylinder of height h_2 are given in Table II-2(c) for $a = 2.66$, various tube diameters, and meniscus heights. The values of V_C - 0.1 given in Table VII are obtained from those of Table II-2(c) by interpolation. In order to reduce the size of the correction δ_6 for the Dead Space 5, we took the standard value V_{5n} to be the volume above a horizontal plane through the index mark in the short arm of the manometer plus 0.1 ml. The temperature variation of V_5 included the variation of the additive 0.1 ml. with temperature. We did not apply a temperature correction to V_C nor to the area of the cylinder $a_5 h_3$ (the largest value of h_3 was 0.16 mm.); nor did we apply a correction for the effect of variations in p' on the volumes of the dead spaces. The effect of these approximations are considered later.

Table VIII gives the equation for computation of the correction δ_6.

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All quantities entering into the calculation have been discussed earlier.

Table IX gives the equation and tables for calculation of the correction δ_7. The values of the coefficient B for nitrogen for the required temperatures were computed from the equation given in Table II-6.

The necessary information for computing the correction δ_8 is given in Table X. The equation for the mean coefficient α_v of thermal pressure increase at constant volume from 0° to 100° C. as a function of the pressure p_0 at 0° is given in Table II-6. This value was used to evaluate $(\partial p/\partial T)_v$ at all temperatures. A discussion of this approximation is given later.

Table XI lists our experimental results and the corrections for the Runs 111 through 394. Each run is a duplicate comparison of the indications of four (in general) standard platinum resistance thermometers with those of two nitrogen gas thermometers, each having approximately the same ice-point pressure. Thus two rows constitute one run. All values to the left of Column 7 apply to both gas thermometers; those to the right apply to the individual gas thermometer, Red or Green. The last column of Table XI gives the final corrected pressure for the nominal temperature given in the first column. These values will be treated in a later paper for determination of the Kelvin temperature of the ice-point and of the thermodynamic Centigrade temperature corresponding to each nominal temperature, the latter being on the International Temperature Scale.

5. EFFECT OF ERRORS

Table XII shows the spread in the values of certain observed quantities throughout each series of runs of the same ice-point pressure. There are also given the values of the observed heights h_2 and h_3 (see Table VII) during the calibrations of the dead space volumes V_5 by the gas expansion method[30].

The corrections δ_4 to δ_7 consist of sums of terms, one for each thermometer space. The values of the individual terms in each summation are given in Table XIII for runs at 600 mm. ice-point pressure and for the bulb temperatures 0°, 100°, and 444.6° C. This gives an idea of the size of the terms entering into each sum.

The corrections δ_4, δ_6, and δ_7 depend explicitly on the Kelvin temperatures of the thermometer bulb and the various dead spaces. The scale assumed in the computation of the corrections is given in Table II-7. Table XIV gives the deviations of this scale from that found in the present investigation and the error (correct minus computed value) introduced into δ_4, δ_6, and δ_7 by the use of an incorrect Kelvin scale for runs at 0°, 100°, and 444.6° C. each for 600 mm. ice-

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point pressure. The error in δ_6 is proportional to the ice-point pressure at each temperature.

Table XV gives the errors produced in H for Run 323 R by the probable errors in the observed quantities, including that produced by optical defects in the manometer tubes.[30] This run is for a nominal bulb temperature of 444.6° C. and an ice-point pressure of 600 mm. where errors produce, in general, the largest effect.

Table XVI lists the errors produced in the pressure p' at the mercury surface in the short arm of the manometer for Run 323 R by the probable errors in the observed quantities and in the properties of materials. The effect of uncertainties in the properties of materials tend to cancel in the computation of gas temperatures since the latter involves ratios of pressures or of differences in pressures.[31] An error in the value of local gravity produces no effect on computed gas temperatures and hence is not considered. Errors in the coefficient of thermal expansion α_s of the scale and the coefficient of thermal dilation α_{Hg} of mercury produce an effect on gas temperatures only in so far as the temperature t_s of the scale and that t_{Hg} of the mercury column vary during a series of runs of the same ice-point pressure. From Table XII we find that in all runs of the same ice-point pressure t_s varies less than 3.5° C. and t_{Hg} less than 0.5° C. The errors given for p' are not those produced in reducing the scale temperature to 20° C. and the mercury column to 0° C. but those introduced in reducing the scale temperature by 3.5° C. (say from 30.5° to 27°) and the mean temperature of the mercury by 0.05° C. (say from 27.5° to 27°).

Table XVII gives the errors in the corrected pressure p for Run 323 R produced by errors in observed quantities and in the properties of materials. The effect of an error in the diameter d_2 of the short arm of the manometer is largely cancelled by the method of calibration of the dead space volume V_5. The value listed in Table XVII is computed for the variation of h_2 and h_3 for Run 323 R from the average values of these quantities during the calibration runs, given in Table XII. In a similar manner uncertainties in the capillary constant a_{Hg} of mercury would largely be eliminated. However, we assumed that a_{Hg} might have varied as much as 1% during the course of the measurements and the effect listed is the total error produced. The rather large error assigned to α_v is caused by the fact that we used the mean value of α_v from 0° to 100° C. at each ice-point pressure for the entire temperature range.

Under Constant Errors of Table XVII are given effects produced by corrections considered but not made. The dead spaces, particularly that in the short arm of the manometer, stretch with increasing internal pressure. This effect could not be measured and the calculation of the stretch is difficult. The theory of elasticity gives the approximate relation:

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$$\Sigma \Delta V_i = 10^{-7} (p' - 760) \text{ ml},$$

where p' is in mm. of mercury and the atmospheric pressure is taken as constant.

Each of the thermometer bulbs was sealed to a pyrex capillary (Dead Space 1) through a graded seal. The volume V_b of the bulb included this graded seal (0.33 ml. for Red system, 0.38 ml. for Green system) and 0.01 ml. of the pyrex capillary. In the computations of V_b as a function of temperature we assumed these spaces to have the coefficient of thermal dilation of vitreous silica. The error shown in Table XVII is computed on the assumption that the coefficient of dilation of the graded seal was the average of those of pyrex glass and vitreous silica.

The errors of the formulas were given in an earlier paper.[31]

As regards the effect of temperature on the volume of the Dead Space 5 we assumed the entire correction including those on a_5 and V_C (see Table VII) was given by making the 0.1 ml. put into the standard volume the same function of temperature as pyrex glass.

In the equation for the volume V_b of the thermometer bulb, Table VII, we assumed that the pressure in the bulb was the same as p'. The largest error is 0.04 mm. (Run 111) and this would have an entirely negligible effect on V_b.

The probable error of the corrected pressure for Run 323 R is 0.013 millimeters of mercury.

6. CORRECTIONS NOT APPLIED

No correction was made for adsorption. Hartley, Henry, and Whytlaw-Gray[35] measured the adsorption of nitrogen on vitreous silica at 21° C. and pressures up to one atmosphere. They found that the adsorbed gas came off rapidly when the pressure was reduced and that the previous history of the surface had no effect on adsorption. Calculations made from their results indicate that if all of the gas adsorbed on the surface of one of our bulbs (area 550 sq. cm., volume 1000 ml.) at 21° C. were given off at 444.6° C. the pressure would be increased 6.6×10^{-4} mm. for an ice-point pressure of 600 mm.

Weber, Keesom, and Schmidt[36] give an equation for the thermomolecular pressure difference and applied it to tubes of 1 to 2 mm. bore filled with helium. Application of the same equation to a tube of 0.71 mm. bore filled with nitrogen gives the result that the pressure differ-

[35] G. A. R. Hartley, T. H. Henry, and R. Whytlaw-Gray, Trans. Faraday Soc., *35*, 1452-61 (1939).

[36] S. Weber, W. H. Keesom, and G. Schmidt, Leiden Comm. No. *246a*, 1-16 (1936).

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ence between 444.6° and 27° C. is 2.5 x 10^{-4} mm. for a pressure of 1572 mm. (ice-point pressure 600 mm.) and 4.6 x 10^{-4} mm. for a pressure of 871 mm. (ice-point pressure 333 mm.).

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7. SUMMARY

A total of 284 comparisons of the indications of four standard platinum resistance thermometers with those of two nitrogen gas thermometers has been made in the temperature range 0° to 444.6° C. The temperatures employed were: 0, 25, 50, 75, 100, 150, 200, 250, 300, 356.58 (mercury boiling point), 400, 444.6° C. (sulphur boiling point). The ice-point pressures in the two gas thermometers were: 1000 (to 100° C. only), 750 (to 150° C. only), 600, 450, 333 mm., approximately. The present paper is concerned with the details of the reduction of the observations to give the corrected pressure in each gas thermometer for each nominal temperature.

A discussion of the effect of errors in observed quantities and in the properties of materials is included.

8. TABLES

TABLE I

Quantities Measured in Each Run

H = vertical distance (mm.) from crown of mercury meniscus in short arm of main manometer to crown in long arm.

h_1 = height (mm.) of mercury meniscus in long arm of main manometer.

h_2 = height (mm.) of meniscus in short arm of main manometer.

h_3 = vertical distance (mm.) from crown of meniscus in short arm of main manometer to index mark in short arm.

t_s = mean temperature (°C. Int.) of the scale.

t_{Hg} = mean temperature (°C. Int.) of mercury in main manometer.

t_b = mean temperature (°C. Int.) of main thermometer bulb.

t_r = nominal temperature (°C. Int.) of the run.

t_i = mean temperature (°C. Int.) of the i-th dead space of the main thermometer system (i = 2,3,4,5).

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TABLE I (Concluded)

H_a = vertical distance (mm.) from crown of mercury meniscus in short arm of auxiliary manometer to crown in long arm.

t_{Hga} = mean temperature (°C.Int.) of mercury in auxiliary manometer.

t_{da} = mean temperature (°C.Int.) of the dead space of the auxiliary thermometer.

H_e = vertical height (mm.) of mercury column in external manometer.

H_B = vertical height (mm.) of mercury column in barometer.

t_e = temperature (°C. Int.) of mercury in external manometer and barometer (mean room temperature).

TABLE II

Calibration Quantities and Properties of Materials

1. Scale

Standard conditions:

The scale was calibrated in a horizontal position at the U. S. National Bureau of Standards.[1] In our measurements it was hung vertically from the 2000 mm. mark.

t_{sn} = 20° C. (Int.), calibration temperature of the scale.

D_2 = 100 mm., scale division nearest to horizontal plane through index mark in short arm of main manometers.

g_n = 980.665 dynes/gm., standard gravity.

(a) Correction for Ruling Error

ϵ = correction at 20° C. The length of an interval is its nominal value plus the correction.

Interval	ϵ	Interval	ϵ
mm.	mm.	mm.	mm.
0 - 100	+0.0014	0 - 1100	+0.0206
0 - 200	.0016	0 - 1200	.0218
0 - 300	.0033	0 - 1300	.0256
0 - 400	.0046	0 - 1400	.0255
0 - 500	.0095	0 - 1500	.0305
0 - 600	.0103	0 - 1600	.0314
0 - 700	.0101	0 - 1700	.0320
0 - 800	.0146	0 - 1800	.0368
0 - 900	.0158	0 - 1900	.0392
0 - 1000	.0172	0 - 2000	.0398

(b) Corrections for Thermal Expansion and for Stretch Caused by its own Weight.

α_S = 1.5 x 10^{-6} °C.$^{-1}$ (Int.), mean coefficient of linear thermal expansion[1] from 20° to t_s °C.

[1,2,3,4] See references at end of Table II.

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TABLE II (Continued)

ρ_s = 8.00×10^{-3} gm./mm.^{3}, density of invar.
E_s = 1.45×10^{10} dynes/mm.^{2}, Young's modulus for invar.
g_l = 980.400 dynes/gm., gravity at the laboratory.

2. Mercury

Standard conditions:

One standard millimeter of mercury is 1/760 of the pressure exerted by a column of mercury in vacuuo at 0° C. and standard gravity, 980.665 dynes/gm.

All pressures are stated in standard mm. of mercury.

(a) Correction for Thermal Dilation and for Compressibility

$\alpha_{Hg} = [181.456 + 9.205 \times 10^{-3} t + 6.608 \times 10^{-6} t^2 + 67.320 \times 10^{-9} t^3] \times 10^{-6}$ °C.$^{-1}$ (Int.), mean coefficient of thermal dilation[2] of mercury from 0° to t° C.

$\beta_{Hg} = 4 \times 10^{-6}$ atm.$^{-1}$, mean coefficient of cubical compressibility of mercury from 0 to 3 atm. at mean room temperature, 27° C.

(b) Correction for the Capillary Depression of Mercury

d = diameter of the manometer tube.
h = height of the mercury meniscus.
a = capillary constant of the mercury.
δ = capillary depression.[3].

d, mm. / h, mm.	20.5	20.6	20.7	20.8	20.9
	δ, mm., for $a = 2.66$ cm.				
0.8	0.0195	0.0191	0.0186	0.0181	0.0177
0.9	.0218	.0213	.0208	.0203	.0198
1.0	.0240	.0234	.0229	.0223	.0218
1.1	.0261	.0255	.0249	.0243	.0237
1.2	.0282	.0276	.0269	.0263	.0256
1.3	.0302	.0295	.0288	.0281	.0274
1.4	.0321	.0314	.0306	.0299	.0291
1.5	.0339	.0331	.0323	.0316	.0308
1.6	.0356	.0348	.0340	.0332	.0323
1.7	.0372	.0364	.0355	.0346	.0337
1.8	.0387	.0378	.0369	.0360	.0351
1.9	.0401	.0392	.0383	.0373	.0364
2.0	.0414	.0404	.0395	.0385	.0376
2.1	.0425	.0415	.0406	.0396	.0386
2.2	.0436	.0425	.0415	.0405	.0395

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TABLE II (Continued)

d, mm. / h, mm.	21.0	21.1	21.2	21.3	21.4	21.5
	δ, mm., for a = 2.66 cm.					
0.8	0.0172	0.0168	0.0164	0.0160	0.0156	0.0152
0.9	.0193	.0188	.0184	.0179	.0175	.0170
1.0	.0213	.0207	.0202	.0197	.0193	.0188
1.1	.0231	.0226	.0221	.0215	.0210	.0205
1.2	.0249	.0243	.0238	.0232	.0226	.0220
1.3	.0267	.0261	.0255	.0248	.0242	.0236
1.4	.0284	.0277	.0271	.0264	.0258	.0251
1.5	.0300	.0293	.0286	.0279	.0272	.0265
1.6	.0315	.0308	.0301	.0293	.0286	.0279
1.7	.0329	.0322	.0314	.0306	.0299	.0291
1.8	.0342	.0334	.0326	.0318	.0311	.0303
1.9	.0355	.0347	.0338	.0330	.0322	.0314
2.0	.0366	.0357	.0349	.0341	.0332	.0324
2.1	.0376	.0367	.0358	.0350	.0341	.0333
2.2	.0385	.0376	.0367	.0358	.0349	.0341

d, mm. / h, mm.	21.0	21.1	21.2	21.3	21.4	21.5
	δ, mm., for a = 2.48 cm.					
0.8	0.0118	0.0115	0.0112	0.0109	0.0106	0.0103
0.9	.0132	.0128	.0125	.0122	.0119	.0115
1.0	.0145	.0141	.0138	.0134	.0130	.0127
1.1	.0157	.0153	.0150	.0146	.0142	.0138
1.2	.0170	.0165	.0161	.0157	.0153	.0149
1.3	.0181	.0177	.0172	.0168	.0163	.0159
1.4	.0192	.0187	.0183	.0178	.0173	.0168
1.5	.0202	.0197	.0192	.0187	.0182	.0177
1.6	.0212	.0207	.0202	.0196	.0191	.0186
1.7	.0221	.0216	.0210	.0205	.0199	.0194
1.8	.0229	.0224	.0218	.0212	.0207	.0201
1.9	.0237	.0231	.0225	.0219	.0213	.0208
2.0	.0244	.0237	.0231	.0225	.0219	.0213
2.1	.0249	.0243	.0237	.0231	.0225	.0218
2.2	.0255	.0248	.0242	.0235	.0229	.0223

(c) Correction for the Variation of the Covolume of the Mercury Meniscus

V_C = the gas volume[3] beneath a horizontal plane through the crown of the meniscus.

b = ratio of V_C to the volume of a cylinder of area equal to that of the manometer tube and height equal to that of the meniscus.

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TABLE II (Continued)

d, mm. / h, mm.	20.5	20.6	20.7	20.8	20.9	21.0
			b for a = 2.66 cm.			
1.0	0.3053	0.3043	0.3033	0.3023	0.3013	0.3003
1.1	.3034	.3024	.3014	.3004	.2994	.2984
1.2	.3013	.3003	.2993	.2983	.2973	.2963
1.3	.2990	.2980	.2970	.2960	.2950	.2940
1.4	.2965	.2955	.2945	.2935	.2925	.2915
1.5	.2937	.2927	.2917	.2907	.2897	.2887
1.6	.2906	.2896	.2886	.2876	.2866	.2856
1.7	.2873	.2863	.2853	.2843	.2833	.2823
1.8	.2838	.2828	.2818	.2808	.2798	.2788
1.9	.2800	.2790	.2780	.2770	.2760	.2750
2.0	.2759	.2749	.2739	.2729	.2719	.2709
2.1	.2716	.2706	.2696	.2686	.2676	.2666
2.2	.2671	.2661	.2651	.2641	.2631	.2621

3. Manometer Tubes of the Main Manometer

d_1 = diameter of long arm of main manometer at the scale mark $H + D_2 = H + 100$ mm.

d_2 = diameter of short arm of main manometer at the scale mark $D_2 = 100$ mm.

a_5 = area of short arm of main manometer at the index mark.

H	d_1 (Red)	d_1 (Green)	H	d_1 (Red)	d_1 (Green)
mm.	mm.	mm.	mm.	mm.	mm.
300	21.05	21.16	1100	21.32	21.06
400	21.23	21.20	1200	21.34	21.15
500	21.26	21.17	1300	21.28	21.23
600	21.35	21.14	1400	21.24	21.29
700	21.39	21.12	1500	21.24	21.26
800	21.39	21.26	1600	21.27	21.19
900	21.34	21.42	1700	21.23	21.17
1000	21.28	21.28			

	Red	Green
d_2 (mm.)	20.823	20.951
a_5 (ml./mm.)	0.3405	0.3447

4. Volumes of the Main Thermometer System

Standard conditions:

t_{bn} = 0° C., standard calibration temperature for the main thermometer bulb.

t_{in} = 27° C. (Int.), standard calibration temperature for the i-th dead space of the main thermometer system (i = 1,2,3,4,5).

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TABLE II (Continued)

The thermometer bulbs were calibrated at an internal and an external pressure of 760 mm. The dead space volumes were assumed independent of internal and external pressure.

(a) Values of the Volumes at Standard Conditions

V_{bn} = volume of the main thermometer bulb at 0° C. and an internal and external pressure of 760 mm.

V_{in} = volume of the i-th dead space at 27° C. (Int.) (i = 1,2,3,4).

V_{5n} = 0.1 ml. plus the volume at 27° C. (Int.) of the fifth dead space above a horizontal plane through the index mark in the short arm of the main manometer.

Thermometer Space	V_n(Red)	V_n(Green)
	ml.	ml.
V_{bn}	986.6958	1015.8008
V^{1n}	0.1991	0.1787
V^{2n}	0.0618	0.0480
V^{3n}	0.1191	0.1109
V^{4n}	0.7700	0.7000
V^{5n}	2.2248	2.4355
	990.0706	1019.2739

(b) Correction for Thermal Dilation and for Pressure Effects

$\alpha_l = (l - l_n)/l_n(t - t_n)$, mean coefficient of linear thermal expansion from t_n to t (l is the length at t, l_n that at t_n).

$\alpha_l' = \frac{1}{l_n}\frac{dl}{dt}$, true coefficient of linear thermal expansion at t.

$\alpha = (V - V_n)/V_n(t - t_n)$, mean coefficient of thermal dilation from t_n to t. (V is volume).

$\alpha' = \frac{1}{V_n}\frac{dV}{dt}$, true coefficient of thermal dilation at t.

Equations:

$$\alpha_l' = \frac{d\left[\alpha_l(t - t_n)\right]}{dt}$$

$$\alpha = 3\alpha_l\left[1 + \alpha_l((t - t_n)\right]$$

$$\alpha' = 3\alpha_l\left[1 + \alpha_l(t - t_n)\right]^2$$

Properties of materials:

$$\alpha_l\ (SiO_2) = \frac{(t + 157.361) \times 10^{-6}}{412.109 + 0.88121t + 0.00126792t^2}\ °C.^{-1}\ (\text{Int.});\ t_n = 0°\,C.$$

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TABLE II (Continued)

$\frac{\beta\,(SiO_2)}{760} = (3.55 - 8 \times 10^{-4}t) \times 10^{-9}$ mm.$^{-1}$; $t =$ °C. (Int.)

α (steel) $= 30 \times 10^{-6}$ °C.$^{-1}$ (Int.); $t_n = 27°$ C. (Int.)

α (stainless steel) $= 48 \times 10^{-6}$ °C.$^{-1}$ (Int.); $t_n = 27°$ C. (Int.)

α (pyrex glass) $= 9.6 \times 10^{-6}$ °C.$^{-1}$ (Int.); $t_n = 27°$ C. (Int.)

Calibration quantities:

α_b = mean coefficient of thermal dilation of the bulb[4] of the main thermometer from 0° to t_r °C. (Int.).

α_b' = true coefficient of thermal dilation of the bulb at t_r °C.

α_i = mean coefficient of thermal dilation of the i-th dead space of the main thermometer system from 27° C. to t_i °C. (Int.) ($i = 1,2,3,4,5$).

β_b = mean coefficient of cubical compressibility[4] of the thermometer bulb from 0 to 3 atm. at t_r °C.

γ_b = mean dilation[4] of the bulb caused by a difference between internal and external pressure $(p' - p_e)$ at t_r °C.

Thermometer Space	Thermometer System	Composition	α °C.$^{-1}$(Int.)	$\frac{\beta}{760}$ mm.$^{-1}$	γ ml./mm.
b	Red	Vitreous Silica	$1.005\alpha(SiO_2)$	$\beta(SiO_2)/760$	$[0.0714\text{-}1.3\times10^{-5}t]\times10^{-3}$
b	Green	Vitreous Silica	$\alpha(SiO_2)$	$\beta(SiO_2)/760$	$[0.0822\text{-}1.3\times10^{-5}t]\times10^{-3}$
1	Both	Pyrex glass	9.6×10^{-6}	----	----
2	Both	Stainless steel	48×10^{-6}	----	----
3	Both	1/3 Stainless steel + 2/3 steel	36×10^{-6}	----	----
4	Both	Stainless steel	48×10^{-6}	----	----
5	Both	1/16 Stainless steel + 15/16 pyrex glass	12×10^{-6}	----	----

5. Lengths

Standard conditions:

All lengths were measured at 27° C. The main gas thermometer bulbs were suspended by rods extending from the junction of the dead spaces 3 and 4 to the thermostat top.

Calibration quantities.

l_{bn} = vertical distance at 27° C. from center of the main thermometer bulb to the beginning of the first dead space.

l_{1n}, l_{2n}, l_{3n} = vertical heights at 27° C. of the consecutive dead spaces 1,2,3 extending from the end of l_b to the point of suspension of the thermometer bulb.

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TABLE II (Continued)

l_4 = vertical height at 27° C. from point of suspension of the thermometer bulb to the point of entrance of the stainless steel capillary into the air thermostat around the main manometer.

l_{5n} = vertical distance at 27° C. from the end of l_4 to a horizontal plane through the index mark in the short arm of the manometer.

(a) Values of the Lengths at Standard Conditions

Space	Length (Red)	Length (Green)
	mm.	mm.
l_{bn}	230	223
l^{1n}	478	456
l^{2n}	157	171
l^{3n}	213	209
l^4	See Table VI	
l_{5n}	-246	-247

(b) Correction for Thermal Expansion of the Lengths

Space	Thermometer System	Composition	Remarks
l_b	Red	200 mm. silica + 30 mm. pyrex	$l_b = l_{bn}$ (0° through 250° C.)
l_b	Green	200 mm. silica + 23 mm. pyrex	$l_b = l_{bn} + 0.1$ (300° through 444.6° C.)
l^1	Both	Pyrex glass	A function of $1/T_1$
l^2	Both	Stainless steel	Constant for all runs
l^3	Both	200 mm. stainless steel, the rest steel	Constant for all runs
l^4	Both		See Table VI
l_5	Both		Constant for all runs

6. Nitrogen

M = 28.016, molecular weight of nitrogen.

R = 62360 ml.-mm./C.° -- mole, the universal gas constant.

B = 73.9548 - 26.5697 x 10^{-3} T - 22.1555 x $10^3/T$ + 80.8487 x $10^6/T^3$ ml./mole, second coefficient of nitrogen in the equation $pV = RT + Bp$, where $T = t$ °C. (Int.) + 273.16.

α_v = $\left[0.003661 + 1.3 \times 10^{-8}\, p_0(\text{mm.})\right]$ °K.$^{-1}$, approximate value of the mean coefficient of thermal pressure increase at constant volume from 0° to 450° C. for nitrogen as a function of the ice-point pressure.

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TABLE II (Concluded)

7. Absolute Temperature Scale for Computing the Corrections

$T\ °K. = t\ °C.\ (Int.) + \Delta$

t °C. (Int.)	Δ	t °C. (Int.)	Δ
0	273.1600	200	273.1950
25	273.1560	250	273.2150
50	273.1550	300	273.2350
75	273.1560	356.58	273.2500
100	273.1600	400	273.2500
150	273.1750	444.6	273.2450

t°C (Int.)	Δ
22.6	273.156
34.2	273.155
65.8	

[1]U. S. National Bureau of Standards, Test No. Twl 54661, Aug. 22, 1928.
[2]Sears, Proc. Phys. Soc. London *26*, 95 (1914).
[3]E. B. Blaisdell, J. Math. and Phys., *19*, 186, 217, 228 (1940).
[4]Reference 32.

TABLE III

Constants of the Platinum Resistance Thermometers

Equations:

$$t = \frac{R_t - R_0}{\alpha R_0} + \delta \left(\frac{t}{100}\right)\left(\frac{t}{100} - 1\right)$$

$$\alpha = \frac{R_w - R_0}{R_0\left[t_w - \delta\left(\frac{t_w}{100}\right)\left(\frac{t_w}{100} - 1\right)\right]}$$

$$\delta = \left(t_s - \frac{R_s - R_0}{\alpha R_0}\right) \Big/ \left(\frac{t_s}{100}\right)\left(\frac{t_s}{100} - 1\right)$$

$$t_0 = 0 - 1.29 \times 10^{-5}\ (B-760) - 0.072 \times 10^{-5}\ h.$$

$$t_w = 100 + 36.8578 \times 10^{-3}(p-760) - 20.159 \times 10^{-6}(p-760)^2 + 16.21 \times 10^{-9}(p-760)^3$$

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TABLE III (Continued)

$t_S = 444.6 + 90.8028 \times 10^{-3}(p-760) - 47.573 \times 10^{-6}(p-760)^2 + 43.61 \times 10^{-9}(p-760)^3$

Quantities:

t, t_0, t_W, t_S = temperatures, °C. (Int.), of the temperature t, the ice point, the steam point, and the sulphur boiling point, respectively.

R_t, R_0, R_W, R_S = resistances of the platinum coil at t, the ice point, the steam point, and the sulphur boiling point, respectively.

α, δ = constants in the Callendar formula.

p = pressure (standard mm. of mercury) at mid-point of platinum coil. For the reduction of the observed height of mercury in the manometer to the pressure p see References 27, 28, and 29.

B = barometric pressure (standard mm. of mercury).

h = distance (mm.) from mid-point of platinum coil to surface of water in the ice-point cell.

Thermometer No.	α	δ	Normal Mercury Boiling Point, °C. (Int.)
	The first figure in parenthesis after each value is the standard deviation of the arithmetic mean in units in the last significant figure and the second is the number of determinations.		
	Calibrations of Dec. 12, 1935: Runs No. 111-135		
107	0.003921 423 (9)(3)	1.492 58 (5)(3)	356.5775 (11)(2)
307	.003919 871 (2)(3)	1.493 54 (15)(3)	356.5732 (4)(2)
308	.003921 771 (14)(3)	1.492 13 (9)(3)	356.5788 (6)(2)
310	.003918 537 (11)(3)	1.495 33 (3)(3)	356.5741 (8)(2)
	Calibrations of Apr. 8, 1936: Runs No. 136-199		
107	0.003921 446 (17)(5)	1.492 37 (6)(2)	
307	.003919 945 (7)(3)	1.493 80 (2)(2)	
308	.003921 838 (0)(3)	1.492 28 (3)(2)	
310	.003918 636 (10)(3)	1.495 91 (15)(2)	
	Calibrations of June 24, 1936: Runs 200-263		
107	0.003921 440 (3)(4)	1.492 64 (0)(2)	
306	.003917 303 (9)(4)	1.494 96 (2)(2)	
307	.003919 845 (13)(5)	1.493 37 (4)(2)	
308	.003921 771 (20)(6)	1.492 15 (21)(2)	
310	.003918 544 (15)(5)	1.495 37 (5)(2)	

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TABLE III (Continued)

Thermometer No.	α	δ	Normal Mercury Boiling Point, °C. (Int.)

The first figure in parenthesis after each value is the standard deviation of the arithmetic mean in units in the last significant figure and the second is the number of determinations.

Calibrations of Sept. 21, 1936: Runs 264-286

107	0.003921 342 (7)(4)	1.493 15 (7)(3)	356.5786 (8)(2)
307	.003919 875 (10)(4)	1.493 91 (5)(3)	356.5791 (11)(2)
308	.003921 778 (14)(4)	1.492 25 (4)(3)	356.5808 (0)(2)
310	.003918 518 (8)(4)	1.495 37 (3)(3)	356.5786 (4)(2)

Calibrations of Oct. 22, 1936: Runs 287-310

107	0.003921 163 (22)(3)	1.492 32 (3)(2)	356.5853 (5)(2)
306	.003917 238 (16)(3)	1.494 86 (16)(2)	356.5774 (21)(4)
307	.003919 840 (11)(2)	1.493 54 (6)(2)	356.5834 (1)(2)
308	.003921 660 (26)(3)	1.491 42 (10)(2)	356.5794 (2)(3)
310	.003918 596 (4)(2)	1.495 59 (15)(2)	356.5832 (6)(2)

Calibrations of Dec. 11, 1936: Runs 311-320

306	0.003917 215 (9)(2)	1.495 54 (4)(2)	356.5782 (12)(2)
307	.003919 919 (14)(2)	1.494 06 (1)(2)	356.5775 (6)(2)
308	.003921 303 (19)(2)	1.493 23 (4)(2)	356.5808 (2)(2)
310	.003918 540 (21)(3)	1.495 15 (3)(2)	356.5791 (17)(2)

Calibrations of Feb. 12, 1937: Runs 321-394

310	0.003918 563 (12)(3)	1.495 08 (11)(3)	356.5707 (9)(3)
312	.003919 338 (20)(3)	1.495 62 (17)(3)	356.5703 (15)(4)
313	.003920 442 (24)(3)	1.494 50 (14)(3)	356.5748 (7)(4)
314	.003920 076 (14)(3)	1.494 46 (10)(3)	356.5698 (8)(3)

Runs in Which the Various Resistance Thermometers Were Used

Therm. No.	107	306	307	308	310	312	313	314
	Run Numbers							
	111-216 252-305	217-251 309-312 315-320	111-320	111-187 190-284 287-312	111-278 283-394	321-394	321-394	321-394

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TABLE III (Concluded)

Dates of Calibrations of the Thermometer Bridge

July, 1935	May, 1937
Dec., 1935	June, 1940
	Sept., 1942

TABLE IV

Reduction of the Observed Mercury Heights to Standard Conditions

Equations:

$$p' = (H + \delta_1 - \delta_2 + \delta_3)F$$

$$\delta_3 = \epsilon_1 - \epsilon_2 + \alpha_s H(t_s - t_{sn}) + \frac{\rho_s g_l}{2E_s} H(H + 2D_2) + \beta_{Hg} H \frac{HF_m - 760}{1520}$$

$$= \left[\epsilon_1 - \epsilon_2 + 1.5 \times 10^{-6} H(t_s - 20) + 2.89 \times 10^{-9} H(H - 673)\right] \text{ mm.}$$

$$F = \frac{g_l}{g_n} \frac{1}{1 + \alpha_{Hg} t_{Hg}}$$

Quantities not defined by the above equations or in Table I or Table II, Parts 1, 2, 3 are given below.

p' = corrected pressure (standard mm. of mercury) at crown of mercury meniscus in the short arm of the main manometer.
δ_1 = capillary depression (mm.) of mercury in long arm of manometer.
δ_2 = capillary depression (mm.) in short arm.
δ_3 = scale corrections and correction (mm.) for the compressibility of mercury.
F_m = 0.995, the value of F at average room temperature of 27 ° C.
ϵ_1 = correction (mm.) for ruling error of scale at reading H + 100 mm.
ϵ_2 = correction (mm.) for ruling error of scale at reading D_2 = 100 mm.
h = height (mm.) of mercury meniscus in long arm of manometer.
h_2' = height (mm.) of mercury meniscus in short arm of manometer.

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TABLE IV (Continued)

Capillary Depression Correction: δ_1
(Interpolated from Table II-2(b) for tube diameters d_1 given in Table II-3)

H, mm. / h_1	300	400	500	600	700	800	900
mm.	δ_1, mm., (Red) for a = 2.66 cm. (Runs 111 to 379)						
0.7	0.0150	0.0144	0.0143	0.0139	0.0138	0.0138	0.0140
0.8	.0170	.0163	.0162	.0158	.0157	.0157	.0159
0.9	.0190	.0182	.0181	.0177	.0175	.0175	.0177
1.0	.0209	.0200	.0199	.0195	.0193	.0193	.0195
1.1	.0228	.0218	.0217	.0212	.0210	.0210	.0212
1.2	.0246	.0235	.0234	.0229	.0226	.0226	.0229
1.3	.0263	.0252	.0250	.0245	.0242	.0242	.0245
1.4	.0280	.0268	.0266	.0260	.0257	.0257	.0260
1.5	.0296	.0283	.0281	.0275	.0272	.0272	.0275
1.6	.0311	.0297	.0295	.0289	.0286	.0286	.0289
1.7	.0325	.0311	.0308	.0302	.0299	.0299	.0302
1.8	.0338	.0323	.0320	.0314	.0311	.0311	.0315
1.9	.0350	.0334	.0332	.0325	.0322	.0322	.0326
2.0	.0361	.0345	.0343	.0335	.0332	.0332	.0336
2.1	.0371	.0355	.0353	.0345	.0341	.0341	.0346
2.2	.0380	.0364	.0361	.0353	.0349	.0349	.0354
2.3	.0388	.0371	.0368	.0360	.0356	.0356	.0361
2.4	.0395	.0377	.0374	.0366	.0363	.0363	.0367
	δ_1, mm., (Green) for a = 2.66 cm. (Runs 111 to 379)						
0.7	0.0146	0.0145	0.0146	0.0147	0.0148	0.0143	0.0137
0.8	.0166	.0164	.0166	.0167	.0168	.0162	.0156
0.9	.0185	.0183	.0185	.0186	.0187	.0181	.0174
1.0	.0204	.0202	.0203	.0205	.0206	.0199	.0192
1.1	.0222	.0220	.0221	.0223	.0224	.0217	.0209
1.2	.0239	.0237	.0239	.0241	.0242	.0234	.0225
1.3	.0256	.0254	.0256	.0258	.0259	.0250	.0241
1.4	.0272	.0270	.0272	.0274	.0275	.0266	.0256
1.5	.0287	.0285	.0287	.0289	.0290	.0281	.0270
1.6	.0302	.0299	.0301	.0304	.0305	.0295	.0284
1.7	.0316	.0313	.0315	.0318	.0319	.0308	.0297
1.8	.0329	.0326	.0328	.0330	.0332	.0320	.0309
1.9	.0340	.0337	.0339	.0342	.0344	.0332	.0320
2.0	.0351	.0348	.0350	.0353	.0355	.0343	.0330
2.1	.0361	.0358	.0360	.0363	.0365	.0353	.0339
2.2	.0370	.0367	.0369	.0372	.0374	.0361	.0347
2.3	.0377	.0374	.0376	.0379	.0381	.0368	.0354
2.4	.0383	.0380	.0382	.0385	.0387	.0374	.0360

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TABLE IV (Continued)

Capillary Depression Correction: δ_1
(Interpolated from Table II-2(b) for tube diameters d_1 given in Table II-3)

H, mm. / h_1	1000	1100	1200	1300	1400	1500	1600	1700
mm.	δ_1, mm., (Red) for a = 2.66 cm. (Runs 111 to 379)							
0.7	0.0142	0.0141	0.0140	0.0142	0.0143	0.0143	0.0142	0.0144
0.8	.0161	.0160	.0159	.0161	.0163	.0163	.0161	.0163
0.9	.0180	.0178	.0177	.0180	.0182	.0182	.0180	.0182
1.0	.0198	.0196	.0195	.0198	.0200	.0200	.0198	.0200
1.1	.0216	.0213	.0212	.0216	.0218	.0218	.0216	.0218
1.2	.0233	.0230	.0229	.0233	.0235	.0235	.0233	.0235
1.3	.0249	.0246	.0245	.0249	.0251	.0251	.0249	.0252
1.4	.0265	.0262	.0260	.0265	.0267	.0267	.0265	.0268
1.5	.0280	.0277	.0275	.0280	.0282	.0282	.0280	.0283
1.6	.0294	.0291	.0289	.0294	.0296	.0296	.0294	.0297
1.7	.0307	.0304	.0302	.0307	.0310	.0310	.0308	.0311
1.8	.0319	.0317	.0315	.0319	.0322	.0322	.0320	.0323
1.9	.0330	.0328	.0326	.0330	.0333	.0333	.0331	.0334
2.0	.0341	.0338	.0336	.0341	.0344	.0344	.0342	.0345
2.1	.0351	.0348	.0346	.0351	.0354	.0354	.0352	.0355
2.2	.0359	.0356	.0354	.0359	.0363	.0363	.0360	.0364
2.3	.0366	.0363	.0361	.0366	.0370	.0370	.0367	.0371
2.4	.0372	.0369	.0367	.0372	.0376	.0376	.0373	.0377
	δ_1 mm., (Green) for a = 2.66 cm. (Runs 111 to 379)							
0.7	0.0142	0.0150	0.0146	0.0144	0.0142	0.0143	0.0145	0.0146
0.8	.0161	.0170	.0166	.0163	.0161	.0162	.0164	.0166
0.9	.0180	.0190	.0185	.0182	.0179	.0181	.0183	.0185
1.0	.0198	.0209	.0204	.0200	.0197	.0199	.0202	.0203
1.1	.0216	.0228	.0222	.0218	.0215	.0217	.0220	.0221
1.2	.0233	.0246	.0240	.0235	.0232	.0234	.0238	.0239
1.3	.0249	.0263	.0257	.0252	.0248	.0250	.0255	.0256
1.4	.0265	.0279	.0273	.0268	.0264	.0266	.0271	.0272
1.5	.0280	.0295	.0288	.0283	.0279	.0281	.0286	.0287
1.6	.0294	.0310	.0303	.0297	.0293	.0295	.0300	.0301
1.7	.0307	.0324	.0317	.0311	.0306	.0308	.0313	.0315
1.8	.0319	.0337	.0330	.0323	.0318	.0320	.0326	.0328
1.9	.0330	.0349	.0341	.0334	.0329	.0332	.0338	.0339
2.0	.0341	.0360	.0352	.0345	.0340	.0343	.0349	.0350
2.1	.0351	.0370	.0362	.0355	.0350	.0353	.0359	.0360
2.2	.0359	.0379	.0371	.0364	.0358	.0361	.0368	.0369
2.3	.0366	.0387	.0378	.0371	.0365	.0368	.0375	.0376
2.4	.0372	.0394	.0384	.0377	.0371	.0374	.0381	.0382

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TABLE IV (Continued)

Capillary Depression Correction: δ_1 *(Continued)*

H, mm / h_1	300	400	500	600	700	800	900
mm.	δ_1, mm., (Red) for a = 2.48 cm. (Runs 380 to 394)						
0.7	0.0103	0.0098	0.0097	0.0095	0.0094	0.0094	0.0095
0.8	.0117	.0111	.0110	.0108	.0107	.0107	.0108
0.9	.0130	.0124	.0123	.0120	.0119	.0119	.0120
1.0	.0143	.0136	.0135	.0132	.0131	.0131	.0132
1.1	.0155	.0148	.0147	.0144	.0142	.0142	.0144
1.2	.0167	.0160	.0158	.0155	.0153	.0153	.0155
1.3	.0179	.0171	.0169	.0166	.0164	.0164	.0166
1.4	.0190	.0181	.0179	.0176	.0174	.0174	.0176
1.5	.0200	.0190	.0188	.0185	.0183	.0183	.0185
1.6	.0209	.0199	.0197	.0194	.0191	.0191	.0194
1.7	.0218	.0208	.0206	.0202	.0199	.0199	.0202
1.8	.0226	.0216	.0214	.0209	.0207	.0207	.0210
1.9	.0233	.0223	.0221	.0216	.0214	.0214	.0217
2.0	.0240	.0229	.0227	.0222	.0220	.0220	.0223
2.1	.0246	.0234	.0232	.0227	.0225	.0225	.0228
2.2	.0251	.0239	.0237	.0231	.0229	.0229	.0232
2.3	.0255	.0243	.0241	.0235	.0233	.0233	.0236
2.4	.0258	.0246	.0244	.0238	.0236	.0236	.0239
	δ_1, mm., (Green) for a = 2.48 cm. (Runs 380 to 394)						
0.7	0.0100	0.0099	0.0100	0.0100	0.0101	0.0097	0.0093
0.8	.0113	.0112	.0113	.0114	.0114	.0110	.0106
0.9	.0126	.0125	.0126	.0127	.0127	.0123	.0118
1.0	.0139	.0138	.0139	.0140	.0140	.0135	.0130
1.1	.0151	.0150	.0151	.0152	.0152	.0147	.0141
1.2	.0163	.0162	.0163	.0164	.0164	.0158	.0152
1.3	.0174	.0173	.0174	.0175	.0175	.0169	.0163
1.4	.0184	.0183	.0184	.0185	.0186	.0179	.0173
1.5	.0194	.0192	.0193	.0195	.0196	.0188	.0182
1.6	.0203	.0201	.0202	.0204	.0205	.0197	.0190
1.7	.0212	.0210	.0211	.0213	.0214	.0206	.0198
1.8	.0220	.0218	.0219	.0221	.0222	.0214	.0205
1.9	.0227	.0225	.0226	.0228	.0229	.0221	.0212
2.0	.0233	.0231	.0232	.0234	.0235	.0227	.0218
2.1	.0238	.0236	.0238	.0240	.0241	.0232	.0223
2.2	.0243	.0241	.0243	.0245	.0246	.0237	.0227
2.3	.0247	.0245	.0247	.0249	.0250	.0241	.0231
2.4	.0250	.0248	.0250	.0252	.0253	.0244	.0234

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TABLE IV (Continued)

Capillary Depression Correction: δ_1 *(Continued)*

H, mm / h_1	1000	1100	1200	1300	1400	1500	1600	1700
mm.	δ_1, mm., (Red) for a = 2.48 cm. (Runs 380 to 394)							
0.7	0.0097	0.0096	0.0095	0.0097	0.0098	0.0098	0.0097	0.0098
0.8	.0110	.0109	.0108	.0110	.0111	.0111	.0110	.0111
0.9	.0122	.0121	.0120	.0122	.0124	.0124	.0123	.0124
1.0	.0134	.0133	.0132	.0134	.0136	.0136	.0135	.0136
1.1	.0146	.0145	.0144	.0146	.0148	.0148	.0147	.0148
1.2	.0157	.0156	.0155	.0157	.0159	.0159	.0158	.0160
1.3	.0168	.0167	.0166	.0168	.0170	.0170	.0169	.0171
1.4	.0178	.0177	.0176	.0178	.0180	.0180	.0179	.0181
1.5	.0187	.0186	.0185	.0187	.0189	.0189	.0188	.0190
1.6	.0196	.0195	.0194	.0196	.0198	.0198	.0197	.0199
1.7	.0205	.0203	.0202	.0205	.0207	.0207	.0206	.0208
1.8	.0213	.0211	.0210	.0213	.0215	.0215	.0214	.0216
1.9	.0220	.0218	.0217	.0220	.0222	.0222	.0221	.0223
2.0	.0226	.0224	.0223	.0226	.0228	.0228	.0227	.0229
2.1	.0231	.0229	.0228	.0231	.0233	.0233	.0232	.0234
2.2	.0235	.0233	.0232	.0235	.0238	.0238	.0237	.0239
2.3	.0239	.0237	.0236	.0239	.0242	.0242	.0240	.0243
2.4	.0242	.0240	.0239	.0242	.0245	.0245	.0243	.0246
	δ_1, mm., (Green) for a = 2.48 cm. (Runs 380 to 394)							
0.7	0.0097	0.0103	0.0100	0.0098	0.0097	0.0097	0.0099	0.0100
0.8	.0110	.0117	.0114	.0111	0.110	.0110	.0112	.0113
0.9	.0122	.0130	.0127	.0124	.0122	.0123	.0125	.0126
1.0	.0134	.0143	.0140	.0136	.0134	.0135	.0138	.0139
1.1	.0146	.0155	.0152	.0148	.0146	.0147	.0150	.0151
1.2	.0157	.0167	.0164	.0160	.0157	.0158	.0162	.0163
1.3	.0168	.0179	.0175	.0171	.0168	.0169	.0173	.0174
1.4	.0178	.0190	.0185	.0181	.0178	.0179	.0183	.0184
1.5	.0187	.0200	.0195	.0190	.0187	.0188	.0192	.0193
1.6	.0196	.0209	.0204	.0199	.0196	.0197	.0201	.0202
1.7	.0205	.0218	.0213	.0208	.0205	.0206	.0210	.0211
1.8	.0213	.0226	.0221	.0216	.0213	.0214	.0218	.0219
1.9	.0220	.0233	.0228	.0223	.0220	.0221	.0225	.0226
2.0	.0226	.0239	.0234	.0229	.0226	.0227	.0231	.0232
2.1	.0231	.0245	.0239	.0234	.0231	.0232	.0237	.0238
2.2	.0235	.0250	.0244	.0239	.0235	.0237	.0242	.0243
2.3	.0239	.0254	.0248	.0243	.0239	.0241	.0246	.0247
2.4	.0242	.0257	.0251	.0246	.0242	.0244	.0249	.0250

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TABLE IV (Continued)

Capilliary Depression Correction: δ_2
(Interpolated from Table II-2(b) for tube diameters d_2 given in Table II-3)

h_2, mm.	1.0	1.1	1.2	1.3	1.4	1.5	1.6
	δ_2, mm., for $a = 2.66$ cm. (All Runs)						
Red	0.0221	0.0241	0.0260	0.0278	0.0296	0.0313	0.0329
Green	.0215	.0234	.0252	.0270	.0287	.0303	.0318

Scale Correction and Correction for the Compressibility of Mercury: δ_3

H, mm. / t s	300	400	500	600	700	800	900
°C. (Int.)			δ_3, mm. (All Runs)				
24	0.0047	0.0102	0.0117	0.0122	0.0175	0.0195	0.0218
25	.0051	.0108	.0124	.0131	.0185	.0207	.0231
26	.0056	.0114	.0132	.0140	.0196	.0219	.0245
27	.0060	.0120	.0139	.0149	.0206	.0231	.0258
28	.0065	.0126	.0147	.0158	.0217	.0243	.0272
29	.0069	.0132	.0154	.0167	.0227	.0255	.0285
30	.0074	.0138	.0162	.0176	.0238	.0267	.0299
31	.0078	.0144	.0169	.0185	.0248	.0279	.0312
32	.0083	.0150	.0177	.0194	.0259	.0291	.0326

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TABLE IV (Continued)

Capillary Depression Correction: δ_2 *(Continued)*
(Interpolated from Table II-2(b) for tube diameters d_2 given in Table II-3)

h_2, mm.	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
	δ_2, mm., for a = 2.66 cm. (All Runs)							
Red	0.0343	0.0357	0.0370	0.0382	0.0393	0.0402	0.0410	0.0417
Green	.0333	.0346	.0358	.0369	.0380	.0389	.0397	.0404

Scale Correction and Correction for the Compressibility of Mercury: δ_3

H, mm. / t_s	1000	1100	1200	1300	1400	1500	1600	1700
°C. (Int.)	δ_3, mm. (All Runs)							
24	0.0261	0.0284	0.0332	0.0343	0.0404	0.0426	0.0445	0.0506
25	.0276	.0300	.0350	.0362	.0425	.0448	.0469	.0532
26	.0291	.0317	.0368	.0382	.0446	.0471	.0493	.0557
27	.0306	.0333	.0386	.0401	.0467	.0493	.0517	.0583
28	.0321	.0350	.0404	.0421	.0488	.0516	.0541	.0608
29	.0336	.0366	.0422	.0440	.0509	.0538	.0565	.0634
30	.0351	.0383	.0440	.0460	.0530	.0561	.0589	.0659
31	.0366	.0399	.0458	.0479	.0551	.0583	.0613	.0685
32	.0381	.0416	.0476	.0499	.0572	.0606	.0637	.0710

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TABLE IV (Concluded)

Factor for the Reduction of Mercury Heights to 0° C. and Standard Gravity

t_{Hg} °C. (Int.)	F
25	.9952 0925
26	.9950 2903
27	.9948 4886
28	.9946 6873
29	.9944 8865
30	.9943 0861

TABLE V

Outline of the Computation of $1/T_1$

Equations:

$$\frac{1}{T_1} = \frac{\frac{\phi_{an}}{p'_a} - \frac{r_{an}}{T_{da}}}{1 - r_{an}}$$

$$p'_a = (H_a + \delta_a)F_a$$

$$\phi_{an} = p'_{an}\left[\frac{1 - r_{an}}{T_{ban}} + \frac{r_{an}}{T_{dan}}\right]$$

Quantities:

Subscript a denotes the auxiliary thermometer system.

Subscript n denotes the value of a quantity at the standard temperature, 27° C. (Int.)

H_a = measured vertical distance (mm.) from the crown of the mercury meniscus in the short arm of the auxiliary manometer to the crown in the long arm.

δ_a = mean value (mm.) of the capillary depression of mercury in the long arm of the auxiliary manometer minus that in the short arm, assumed constant for all runs.

F_a = factor for reducing mercury heights from a temperature t_{Hga} to 0° C. and standard gravity, see Table IV.

p'_a = pressure (standard mm. of mercury) at the crown of the mercury meniscus in the short arm of the auxiliary manometer.

r_{an} = ratio of the volume of the dead space of the auxiliary thermometer to the total volume at standard conditions, 27° C. (Int.).

T_{ba} = temperature (°K.) of the auxiliary thermometer bulb.

T_{da} = temperature (°K.) of the auxiliary thermometer dead space.

ϕ_{an} = calibration function of the auxiliary thermometer. In the calibration, the temperature T_{ban} of the thermometer bulb is maintained at 27° C. in a thermostat, the mean temperature T_{dan} of the dead space is approximately 27° C., but measured exactly, and p'_{an} is the corrected pressure.

$1/T_1$ = reciprocal temperature (°K.$^{-1}$) averaged with respect to area for the portion of the main thermometer system in the region of large thermal gradient.

Details of compution of the numerical values of $1/T_1$ are not given, but the results are listed in Table XI.

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TABLE VI

The Gravitational Correction: δ_4

Equations:

$$\delta_4 = 1.1795 \times 10^{-6} M \frac{p' V_b}{V} \left(\frac{l_b}{T_b} + \sum_1^5{}_i \frac{l_i}{T_i} \right)$$

$$= 3.3045 \times 10^{-5} \frac{p' V_b}{V} \left(\frac{l_b}{T_b} + \sum_1^5{}_i \frac{l_i}{T_i} \right)$$

Quantities:

M = 28.016, molecular weight of nitrogen, Table II-6.

p' = corrected pressure (standard mm. of mercury) at crown of mercury meniscus in short arm of main manometer; listed in Table XI.

T = approximate Kelvin temperature of the bulb (T_b) or of the i-th dead space (T_i). The relation for conversion of t° C. (Int.) to T °K. is given in Table II-7. The nominal temperature t_r of the run was used for t_b; $1/T_1$ was determined directly by the auxiliary thermometer by the method outlined in Table V and is listed in Table XI; t_2 to t_5 are listed in Table XI.

l_b [l_i] = vertical height (mm.) of the bulb [i-th dead] space, see Table II-5. They are tabulated below.

h_3 = vertical distance (mm.) from the index mark in the short arm of the main manometer to the crown of the mercury meniscus, listed in Table XI.

V_b = volume of the main thermometer bulb under the conditions of the run, Table VII.

V = volume of the main thermometer system under standard conditions, Table II-4(a).

Runs 111 through 251 were made in the oil thermostat; Runs 252 through 394 in the nitrate thermostat.

t_r	l_b/T_b, mm./°K.		l_4, mm.	
°C. (Int.)	Red	Green	Red	Green
0	0.84200	0.81637	-480.8	-480.8
25	.77141	.74793	-481.0	-481.0
50	.71173	.69007	-481.2	-481.2
75	.66062	.64052	-481.4	-481.4
100	.61636	.59760	-481.7	-481.7
150 (oil thermostat)	.54351	.52697	-482.1	-482.1
150 (nitrate thermostat)	.54351	.52697	-570.5	-532.5
200	.48606	.47126	-571.0	-533.0
250	.43959	.42621	-571.5	-533.5
300	.40141	.38919	-572.0	-534.0
356.58	.36534	.35422	-572.6	-534.6
400	.34177	.33138	-573.0	-535.0
444.6	.32054	.31079	-573.5	-535.5

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TABLE VI (Concluded)

Red		Green		Red		Green
$1/T_1$	l_1	$1/T_1$	l_1	(All runs)		
$^\circ K.^{-1}$	mm.	$^\circ K.^{-1}$	mm.	l_2 (mm.)	157.0	171.0
0.001890	478.3	0.001851	456.3	l_3 (mm.)	213.0	209.0
.002156	478.2	.002120	456.2	l_5 (mm.)	$-246.0-h_3$	$-247.0-h_3$
.002511	478.1	.002481	456.1			
.003004	478.0	.002990	456.0			
.003738		.003760				

TABLE VII

The Correction for Variation in Volume of the System on the Assumption that the Gas is Ideal: δ_5

Equations:

$$\delta_5 = \frac{p'}{V}\left[(V_b - V_{bn}) + \sum_2^5 i\ (V_i - V_{in})\right]$$

$$V = V_{bn} + \sum_1^5 i\ V_{in}$$

$$V_b - V_{bn} = V_{bn}\left[\alpha_b(t_r - t_{bn}) + \alpha'_b(t_b - t_r) - \frac{\beta_b}{760}(p'-760)\right] + \gamma_b(p' - p_e)$$

$$V_i - V_{in} = V_{in}\,\alpha_i(t_i - t_{in}) \qquad (i = 2,3,4)$$

$$V_5 - V_{5n} = V_{5n}\alpha_5\ (t_5 - t_{5n}) + a_5 h_3 + (V_C - 0.1)$$

$$p' - p_e = HF - (H_e + H_B)F_e$$

Quantities:

p' is listed in Table XI.

$p'-p_e$ is listed in Table XI. It is computed from the (approximate) equations given above. H, H_e, H_B are measured quantities (see Table I), and F $[F_e]$ are the factors to reduce mercury heights to standard conditions given in Table IV for the temperatures t_{H_β} $[t_e]$ of Table I.

V, V_{bn}, V_{in} $(i = 1,2,3,4,5)$ are given in Table II-4(a).

V_b = volume (ml.) of the main thermometer bulb at the bulb temperature t_b, internal pressure p', and external pressure p_e. The temperature effect is computed in two steps: calculation is first made of the dilation to the nominal

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TABLE VII (Continued)

temperature t_r of the run and then a small correction is applied for the deviation of t_b from t_r.

V_i = volume (ml.) of the i-th dead space (i = 1,2,3,4,5) under the conditions of the run.

α_b, α'_b, β_b, γ_b, α_i (i = 2,3,4,5) are given in Table II-4(b).

t_{bn}, t_{in}, (i = 2,3,4,5) are given in Table II-4

t_b, t_i (i = 2,3,4,5) are given in Table XI.

a_5 is given in Table II-3.

h_2 and h_3 are given in Table XI.

V_C is listed in terms of b in Table II-2(c).

Main Thermometer Bulb Volumes
(See Table II-4)

t_r °C. (Int.)	$10^3 \times V_{bn}\alpha_b t_r$ ml.	$10^3 \times V_{bn}\alpha'_b$ ml./°C.	$10^3 \times V_{bn}\beta_b/760$ ml./mm.	$10^3 \times \gamma_b$ ml./mm.
		Red thermometer bulb		
0	0.0	1.14	0.003503	0.0714
25	31.18	1.35	.003483	.0711
50	67.15	1.52	.003463	.0708
75	106.83	1.65	.003444	.0704
100	149.28	1.74	.003424	.0701
150	239.46	1.85	.003384	.0694
200	332.74	1.87	.003345	.0688
250	425.78	1.84	.003305	.0682
300	516.39	1.78	.003266	.0675
356.58	614.38	1.68	.003221	.0668
400	685.70	1.60	.003187	.0662
444.6	755.20	1.52	.003152	.0656
		Green thermometer bulb		
0	0.0	1.16	0.003606	0.0822
25	31.94	1.38	.003586	.0819
50	68.79	1.56	.003565	.0816
75	109.43	1.69	.003545	.0812
100	152.92	1.79	.003525	.0809
150	245.29	1.89	.003484	.0802
200	340.85	1.92	.003444	.0796
250	436.15	1.89	.003403	.0790
300	528.98	1.82	.003362	.0783
356.58	629.36	1.72	.003316	.0776
400	702.41	1.64	.003281	.0770
444.6	773.61	1.55	.003245	.0764

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TABLE VII (Continued)

Main Thermometer Dead Space Volumes
(See Table II-4 and Table II-2(c).)

$\Delta V_i = V_{in}\alpha_i(t_i - 27)$

t_2 °C. (Int.)	$10^3 \times \Delta V_2$ ml.	t_3 °C. (Int.)	$10^3 \times \Delta V_3$ ml.	t_4 °C. (Int.)	$10^3 \times \Delta V_4$ ml.	t_4 °C. (Int.)	$10^3 \times \Delta V_4$ ml.	t_5 °C. (Int.)	$10^3 \times \Delta V_5$ ml.	h_2 mm.	$10^3 \times (V_C - 0.1)$ ml.
Red Thermometer System											
21.9	-0.01	23.5	-0.01	24.97	-0.07	28.76	+0.07	24.940	-0.05	1.20	21.8
25.3	± .00	25.8	± .00	25.24	- .06	29.03	.08	25.314	- .04	1.25	26.4
28.7	+ .01	28.2	+ .01	25.51	- .05	29.30	.09	25.689	- .03	1.30	30.9
32.1	.02	30.5	.02	25.78	- .04	29.57	.10	26.064	- .02	1.35	35.4
35.4	.03	32.8	.03	26.05	- .03	29.84	.11	26.438	- .01	1.40	39.8
38.8		35.2		26.32	- .02	30.11	.12	26.813	+ .00	1.45	44.1
				26.59	- .01	30.38	.13	27.187	+ .01	1.50	48.3
				26.86	± .00	30.65	.14	27.562	.02	1.55	52.5
				27.14	+ .01	30.92	.15	27.936	.03	1.60	56.6
				27.41	.02	31.19	.16	28.311	.04	1.65	60.6
				27.68	.03	31.46	.17	28.686	.05	1.70	64.5
				27.95	.04	31.73	.18	29.060	.06	1.75	68.3
				28.22	.05	32.01	.19	29.435	.07	1.80	72.0
				28.49	.06	32.28		29.809	.08	1.85	75.6
				28.76				30.184		1.90	79.1
										1.95	82.5
										2.00	85.8

a_5(Red) = 0.3405 ml./mm.

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TABLE VII (Continued)

$\Delta V_i = V_{in}\alpha_i(t_i - 27)$ (Continued)

t_2 °C. (Int.)	$10^3 \times \Delta V_2$ ml.	t_3 °C. (Int.)	$10^3 \times \Delta V_3$ ml.	t_4 °C. (Int.)	$10^3 \times \Delta V_4$ ml.	t_4 °C. (Int.)	$10^3 \times \Delta V_4$ ml.	t_5 °C. (Int.)	$10^3 \times \Delta V_5$ ml.	h_2 mm.	$10^3 \times (V_C - 0.1)$ ml.
Green Thermometer System											
24.8		23.2		24.77		28.64		25.118		1.20	22.8
	±0.00		-0.01		-0.07		+0.06		-0.05		
29.2		25.7		25.07		28.93		25.460		1.25	27.4
	+ .01		± .00		- .06		.07		- .04		
33.5		28.3		25.36		29.23		25.802		1.30	32.0
	.02		+ .01		- .05		.08		- .03		
37.9		30.8		25.66		29.53		26.145		1.35	36.5
			.02		- .04		.09		- .02		
		33.3		25.96		29.83		26.487		1.40	40.9
					- .03		.10		- .01		
				26.26		30.12		26.829		1.45	45.2
					- .02		.11		+ .00		
				26.55		30.42		27.171		1.50	49.5
					- .01		.12		+ .01		
				26.85		30.72		27.513		1.55	53.7
					± .00		.13		.02		
				27.15		31.02		27.855		1.60	57.8
					+ .01		.14		.03		
				27.45		31.32		28.198		1.65	61.8
					.02		.15		.04		
				27.74		31.61		28.540		1.70	65.8
					.03		.16		.05		
				28.04		31.91		28.882		1.75	69.7
					.04		.17		.06		
				28.34		32.21		29.224		1.80	73.4
					.05				.07		
				28.64				29.566		1.85	77.0
									.08		
								29.908		1.90	80.5
									.09		
								30.251		1.95	83.9
										2.00	87.2

a_5 (Green) = 0.3447 ml./mm.

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TABLE VIII

The Corrections for Variation of Temperature of the System on the Assumption that the Gas is Ideal: δ_6

Equation:

$$\delta_6 = \frac{p'}{V}\left[V_{in}\left(\frac{T_b}{T_1} - 1\right) + \sum_{2}^{5} {}_1 V_i \left(\frac{T_b}{T_i} - 1\right)\right]$$

Quantities:

V_{in} is given in Table II-4(a).

The computation of V_i $(i = 2,3,4,5)$ is given in Table VII.

The computation of $1/T_1$ is outlined in Table V and the values of $1/T_1$ are given in Table XI.

Approximate values of T_b, T_i $(i = 2,3,4,5)$ are computed from the values of t_b, t_i $(i = 2,3,4,5)$ listed in Table XI by the method given in Table II-7.

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TABLE IX

The Correction to $(\delta_5 + \delta_6)$ for the Imperfection of the Gas: δ_7

Equation:

$$\delta_7 = \frac{p'^2}{RV}\left[B_r\left(\frac{V_b - V}{T_r} + 2\sum_1^5 i\,\frac{V_i}{T_i}\right) - T_r\sum_1^5 \frac{B_i V_i}{T_i^2}\right],$$

where V_i signifies V_{in} for $i = 1$.

Quantities:

R is given in Table II-6.

B_r $\left[B_i\right]$ = second "virial coefficient" for nitrogen (ml./mole) at t_r $\left[t_i\right]$, see Table II-6.

Volumes and temperatures are explained in Table VII and VIII.

Values of the Second Coefficient B for Nitrogen
(See Table II-6)

t_r °C. (Int.)	B_r ml./mole	$1/T_1$ °K.$^{-1}$	B_1 ml./mole	t_i °C. (Int.)	B_i ml./mole
0	-10.445	0.0035	- 7.714	25	-5.224
25	- 5.224	.0034	- 6.011	26	-5.033
50	- 0.795	.0033	- 4.304	27	-4.843
75	+ 2.984	.0032	- 2.597	28	-4.654
100	6.223	.0031	- 0.890	29	-4.467
150	11.421	.0030	+ 0.815	30	-4.280
200	15.322	.0029	2.514	31	-4.095
250	18.270	.0028	4.205	32	-3.911
300	20.500	.0027	5.886	33	-3.728
356.58	22.364	.0026	7.552	34	-3.547
400	23.421	.0025	9.201	35	-3.366
444.6	24.235	.0024	10.829	36	-3.187
		.0023	12.429	37	-3.009
		.0022	13.996		
		.0021	15.525		
		.0020	17.006		

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TABLE IX (Continued)

Values of $2V_i/T_i$

$1/T_1$ °K.$^{-1}$	$10^4 \times 2V_{1n}/T_1$ ml./°K.	t_i °C. (Int.)	$10^4 \times 2V_2/T_2$ ml./°K.	$10^4 \times 2V_3/T_3$ ml./°K.	$10^4 \times 2V_4/T_4$ ml./°K.	$10^4 \times 2V_5/T_5$ ml./°K.
			Red Thermometer System			
0.0035	13.94	25	4.14	7.99	51.65	149.23
.0034	13.54	26	4.13	7.96	51.48	148.74
.0033	13.14	27	4.12	7.94	51.31	148.24
.0032	12.74	28	4.10	7.91	51.14	147.75
.0031	12.34	29	4.09	7.88	50.97	147.27
.0030	11.95	30	4.08	7.86	50.81	146.78
.0029	11.55	31	4.06	7.83	50.64	
.0028	11.15	32	4.05	7.81	50.48	
.0027	10.75	33	4.04	7.78		
.0026	10.35	34	4.03			
.0025	9.96	35	4.01			
.0024	9.56	36	4.00			
.0023	9.16	37	3.99			
.0022	8.76					
.0021	8.36					
.0020	7.96					
			Green Thermometer System			
0.0035	12.51	25	3.22	7.44	46.95	163.37
.0034	12.15	26	3.21	7.41	46.80	162.82
.0033	11.79	27	3.20	7.39	46.64	162.28
.0032	11.44	28	3.19	7.36	46.49	161.75
.0031	11.08	29	3.18	7.34	46.34	161.21
.0030	10.72	30	3.17	7.32	46.19	160.68
.0029	10.36	31	3.16	7.29	46.04	
.0028	10.01	32	3.15	7.27	45.89	
.0027	9.65	33	3.14	7.25		
.0026	9.29	34	3.13			
.0025	8.94	35	3.12			
.0024	8.58	36	3.11			
.0023	8.22	37	3.10			
.0022	7.86					
.0021	7.51					
.0020	7.15					

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TABLE IX (Continued)

Values of $V_i B_i / T_i^2$

$1/T_1$	$10^4 \times \frac{V_{1n} B_1}{T_1^2}$	t_i	$10^4 \times \frac{V_2 B_2}{T_2^2}$	$10^4 \times \frac{V_3 B_3}{T_3^2}$	$10^4 \times \frac{V_4 B_4}{T_4^2}$	$10^4 \times \frac{V_5 B_5}{T_5^2}$
°K.$^{-1}$	ml./mole-°K.^{2}	°C. (Int.)	ml./mole-°K.^{2}			
			Red Thermometer System			
0.0035	-0.189	25	-0.036	-0.070	-0.452	-1.307
.0034	- .139	26	- .035	- .067	- .433	-1.251
.0033	- .094	27	- .033	- .064	- .414	-1.196
.0032	- .053	28	- .032	- .061	- .395	-1.142
.0031	- .017	29	- .030	- .058	- .377	-1.089
.0030	+ .015	30	- .029	- .055	- .359	-1.036
.0029	.042	31	- .027	- .053	- .341	
.0028	.065	32	- .026	- .050	- .323	
.0027	.085	33	- .025	- .047		
.0026	.101	34	- .023			
.0025	.114	35	- .022			
.0024	.124	36	- .021			
.0023	.131	37	- .019			
.0022	.135					
.0021	.136					
.0020	.137					
			Green Thermometer System			
0.0035	-0.169	25	-0.028	-0.065	-0.411	-1.431
.0034	- .124	26	- .027	- .062	- .394	-1.370
.0033	- .084	27	- .026	- .060	- .376	-1.309
.0032	- .048	28	- .025	- .057	- .359	-1.250
.0031	- .016	29	- .023	- .054	- .343	-1.192
.0030	+ .013	30	- .022	- .052	- .326	-1.134
.0029	.038	31	- .021	- .049	- .310	
.0028	.060	32	- .020	- .047	- .294	
.0027	.078	33	- .019	- .044		
.0026	.092	34	- .018			
.0025	.103	35	- .017			
.0024	.111	36	- .016			
.0023	.117	37	- .015			
.0022	.121					
.0021	.122					
.0020	.123					

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TABLE X

The Correction to the Nominal Temperature of the Run: δ_8

Equations:

$$\delta_8 = \alpha_v p_0 (t_r - t_b)$$

$$\alpha_v = \left[0.003661 + 1.3 \times 10^{-8} p_0 \text{ (mm.)}\right] {}^\circ K.^{-1}$$

Quantities:

For α_v see Table II-7.

t_r = nominal temperature (°C. Int.) of the main thermometer bulb.

t_b = actual temperature (°C. Int.) of the main thermometer bulb.

p_0 = average ice-point pressure (standard mm. of mercury) for a series of runs, see Table XI.

Runs	$\alpha_v p_0$ mm./°K.	
	Red	Green
111–135	3.668	3.672
136-167	2.752	2.757
168-199	1.648	1.651
200-225	2.200	2.202
226-308	1.221	1.225
309-356	2.203	2.205
357-394	1.649	1.651

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TABLE XI

Reduction of the Observations

Equations: $p' = (H + \delta_1 - \delta_2 + \delta_3)F$

$p = p' + \delta_4 + \delta_5 + \delta_6 + \delta_7 + \delta_8$

See Tables I and III to X.

Column	Quantity Listed
1	t_r = temperature (°C. Int.) of run. p_0 = approximate ice-point pressure (mm. *Hg*).
2	Run number. Date.
3-4	t_b = bulb temperature (°C. Int.) determined by platinum resistance thermometer identified in parenthesis. (Table III)
5	t_b (ave.) = mean of the values of Columns 3-4. Ave. dev. = average deviation (°C. Int.) of mean.
6	t_s = scale temperature (°C. Int.) t_{Hg} = temperature (°C. Int.) of mercury column in main manometer.
7	R = Red gas thermometer. G = Green gas thermometer.
8	H = vertical height (mm.) of mercury column in main manometer.
9	h_1 = height (mm.) of mercury meniscus in long arm of main manometer.
10	h_2 = height (mm.) of mercury meniscus in short arm of main manometer.
11	h_3 = vertical distance (mm.) from crown of mercury meniscus to index mark in short arm of main manometer.
12	δ_1 = capillary depression (mm.) of mercury in long arm of main manometer. (Table IV)
13	δ_2 = capillary depression (mm.) of mercury in short arm. (Table IV)
14	δ_3 = scale correction and correction for compressibility of mercury (mm.). (Table IV)

t_r / p_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
0	111	-0.0096	-0.0100	-0.0098	25.60	R	1003.2992	1.110	1.841	0.0543	0.0218	0.0362	0.0286
1000	2/27/36	-0.0098	-0.0098	0.0001	25.580	G	1004.6330	1.109	1.704	0.0465	0.0218	0.0334	0.0286
0	112	+0.0014	+0.0017	+0.0020	25.30	R	1003.3422	1.099	1.908	0.0587	0.0216	0.0371	0.0281
1000	2/28/36	+0.0019	+0.0030	0.0005	25.553	G	1004.6757	1.022	1.696	0.0580	0.0202	0.0332	0.0282
0	113	-0.0020	-0.0021	-0.0018	25.19	R	1003.3092	1.111	1.940	0.0975	0.0218	0.0375	0.0280
1000	2/28/36	-0.0017	-0.0014	0.0002	25.544	G	1004.6623	1.091	1.658	0.0492	0.0215	0.0327	0.0280
100	114	100.0013	100.0016	100.0006	25.52	R	1370.1758	1.142	1.927	0.0743	0.0225	0.0373	0.0417
1000	3/2/36	99.9981	100.0014	0.0012	25.516	G	1372.0290	1.087	1.686	0.0488	0.0214	0.0331	0.0418

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TABLE XI (Continued)

Reduction of the Observations

Two rows constitute a run. Columns 1-6 apply to both gas thermometers which are identified in Column 7 as *R* (Red) and *G* (Green). Columns 8-27 give the results for the gas thermometer indicated in Column 7.

Column	Quantity Listed
15	p' = pressure (standard mm. *Hg*) at crown of meniscus in short arm of main manometer.
16	$p'-p_e$ = excess of internal over external pressure (mm. *Hg*) for the thermometer bulb.
17	$1/T_1$ = reciprocal Kelvin temperature (°Abs.) averaged with respect to area for Dead Space 1. (Table V)
18-21	t_2, t_3, t_4, t_5 = temperature (°C. Int.) of Dead Spaces 2,3,4,5, respectively.
22	δ_4 = gravitational correction (stand. mm. Hg). (Table VI)
23	δ_5 = correction (stand. mm. *Hg*) for volume variation of the system on assumption gas is ideal. (Table VII)
24	δ_6 = correction (stand. mm. *Hg*) for temperature variation of the system on assumption gas is ideal. (Table VIII)
25	δ_7 = correction (stand. mm. *Hg*) to $\delta_6 + \delta_7$ for imperfection of gas. (Table IX)
26	δ_8 = correction (stand. mm. *Hg*) to nominal temperature of run. (Table X)
27	p = pressure (stand. mm. *Hg*) of gas thermometer at nominal temperature t_r given in Column 1.

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
998.4019	-5	0.003452	26.0	26.0	25.60	25.594	0.0426	0.0929	-0.2942	-0.0009	0.0359	998.278
999.7320	-4	0.003456	25.0	25.8	25.60	25.594	0.0405	0.0793	-0.2936	-0.0009	0.0360	999.593
998.4480	-6	0.003464	26.0	26.0	25.27	25.554	0.0427	0.0991	-0.2929	-0.0009	-0.0073	998.289
999.7775	-4	0.003473	25.0	25.0	25.39	25.554	0.0407	0.0826	-0.2919	-0.0009	-0.0073	999.601
998.4165	-6	0.003466	26.0	25.3	25.21	25.545	0.0428	0.1146	-0.2936	-0.0010	0.0066	998.286
999.7674	-3	0.003473	25.0	25.0	25.28	25.545	0.0407	0.0767	-0.2912	-0.0009	0.0066	999.599
1363.5110	-3	0.002984	31.0	27.0	25.44	25.526	0.0374	0.03486	1.1556	0.0048	-0.0022	1365.055
1365.3583	+1	0.002999	30.0	27.2	25.51	25.526	0.0353	0.3112	1.1540	0.0048	-0.0022	1366.861

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TABLE XI (Continued)

t_r P_o	Run No. Date	t_b(308) t_b(307)	t_b(107) t_b(310)	t_b(ave.) Ave. dev.	t_s t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
100	115	100.0019	100.0016	100.0010	25.42	R	1370.1905	1.103	1.966	0.0613	0.0218	0.0378	0.0415
1000	3/3/36	100.0001	100.0004	0.0008	25.534	G	1372.0302	0.983	1.767	0.0662	0.0195	0.0342	0.0416
0	116	-0.0029	-0.0032	-0.0032	25.42	R	1003.3115	1.123	1.831	0.0808	0.0220	0.0361	0.0283
1000	3/6/36	-0.0028	-0.0038	0.0003	25.524	G	1004.6312	1.117	1.775	0.0703	0.0219	0.0343	0.0283
0	117	-0.0051	-0.0046	-0.0048	25.50	R	1003.3067	1.102	1.875	0.0510	0.0216	0.0367	0.0284
1000	3/6/36	-0.0046	-0.0051	0.0002	25.534	G	1004.6128	0.992	1.746	0.1127	0.0197	0.0339	0.0285
100	118	100.0011	100.0014	100.0000	25.37	R	1370.1815	1.147	1.980	0.0715	0.0225	0.0380	0.0414
1000	3/9/36	99.9988	99.9989	0.0012	25.502	G	1372.0177	1.075	1.731	0.0427	0.0211	0.0337	0.0415
100	119	100.0005	100.0008	99.9994	25.59	R	1370.1828	1.137	1.791	0.0485	0.0224	0.0356	0.0418
1000	3/9/36	99.9982	99.9980	0.0013	24.541	G	1372.0005	1.011	1.735	0.0610	0.0200	0.0338	0.0420
0	120	+0.0048	+0.0057	+0.0052	25.37	R	1003.3474	1.149	1.794	0.0532	0.0224	0.0356	0.0282
1000	3/11/36	+0.0049	+0.0055	0.0004	25.568	G	1004.6768	1.178	1.622	0.0572	0.0230	0.0321	0.0283
0	121	+0.0003	+0.0004	+0.0003	25.30	R	1003.3272	1.163	1.807	0.1027	0.0227	0.0358	0.0281
1000	3/11/36	+0.0004	+0.0000	0.0001	25.558	G	1004.6615	1.090	1.612	0.0645	0.0215	0.0320	0.0282
100	122	100.0023	100.0026	100.0036	25.84	R	1370.1708	1.130	1.784	0.1312	0.0223	0.0355	0.0424
1000	3/14/36	100.0038	100.0057	0.0012	25.582	G	1371.9973	0.947	1.627	0.1407	0.0188	0.0322	0.0425
75	123	74.9957	74.9955	74.9965	25.87	R	1278.5542	1.013	1.830	0.0510	0.0200	0.0361	0.0376
1000	3/16/36	74.9982	74.9967	0.0009	25.580	G	1280.2387	0.899	1.753	0.0868	0.0182	0.0340	0.0377
50	124	50.0025	50.0019	50.0025	26.07	R	1186.8885	1.085	1.794	0.0827	0.0210	0.0356	0.0363
1000	3/16/36	50.0028	50.0027	0.0003	25.667	G	1188.4935	1.046	1.746	0.0432	0.0213	0.0339	0.0363
25	125	25.0032	25.0040	25.0034	26.05	R	1095.1578	1.144	1.840	0.0520	0.0221	0.0362	0.0317
1000	3/17/36	25.0030	25.0034	0.0003	25.633	G	1096.5963	1.022	1.683	0.0792	0.0213	0.0330	0.0317
25	126	25.0031	25.0036	25.0030	25.94	R	1095.1400	1.207	1.825	0.0720	0.0231	0.0360	0.0315
1000	3/17/36	25.0025	25.0030	0.0003	25.617	G	1096.5908	1.100	1.752	0.0947	0.0228	0.0340	0.0315
75	127	75.0018	75.0030	75.0035	25.75	R	1278.5358	1.142	1.816	0.1022	0.0222	0.0359	0.0374
1000	3/18/36	75.0053	75.0038	0.0011	25.497	G	1280.2240	1.086	1.491	0.1425	0.0216	0.0302	0.0374
50	128	50.0031	50.0026	50.0036	25.77	R	1186.8753	1.114	1.792	0.0488	0.0215	0.0356	0.0357
1000	3/18/36	50.0049	50.0036	0.0007	25.524	G	1188.4562	1.110	1.583	0.0612	0.0224	0.0315	0.0358
100	129	100.0010	100.0008	100.0003	25.49	R	1370.1558	1.159	1.840	0.1323	0.0227	0.0362	0.0416
1000	3/19/36	99.9982	100.0012	0.0010	25.506	G	1372.0040	1.106	1.446	0.1015	0.0217	0.0294	0.0418
0	130	-0.0030	-0.0033	-0.0026	25.29	R	1003.3127	1.138	1.927	0.0503	0.0222	0.0373	0.0281
1000	3/23/36	-0.0023	-0.0017	0.0006	25.498	G	1004.6445	1.131	1.514	0.0568	0.0222	0.0305	0.0281
0	131	0.0000	-0.0006	+0.0001	25.22	R	1003.3170	1.184	1.823	0.0483	0.0230	0.0360	0.0280
1000	3/23/36	+0.0005	+0.0006	0.0004	25.482	G	1004.6458	1.186	1.770	0.0532	0.0231	0.0342	0.0280
100	132	100.0011	100.0035	100.0012	25.52	R	1370.1663	1.077	1.904	0.0965	0.0213	0.0370	0.0417
1000	3/24/36	100.0000	100.0004	0.0011	25.481	G	1371.9883	1.016	1.760	0.0810	0.0201	0.0341	0.0418
100	133	100.0012	100.0033	100.0028	25.37	R	1370.1573	1.160	1.832	0.1022	0.0228	0.0361	0.0414
1000	3/24/36	100.0035	100.0034	0.0008	25.483	G	1371.9902	1.145	1.667	0.0825	0.0223	0.0328	0.0415

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
1363.5198	-2	0.002997	30.0	27.0	25.35	25.547	0.0377	0.3462	1.1568	0.0048	-0.0037	1365.062
1365.3519	-1	0.003003	30.0	27.0	25.55	25.547	0.0354	0.3274	1.1581	0.0048	-0.0037	1366.874
998.4243	-6	0.003467	26.0	26.0	25.38	25.528	0.0428	0.1012	-0.2930	-0.0009	0.0117	998.286
999.7392	-1	0.003472	25.0	25.0	25.42	25.528	0.0407	0.0929	-0.2927	-0.0009	0.0118	999.591
998.4168	-6	0.003467	26.0	26.0	25.46	25.543	0.0428	0.0941	-0.2927	-0.0009	0.0176	998.278
999.7175	0	0.003472	25.0	25.0	25.52	25.543	0.0407	0.1052	-0.2941	-0.0010	0.0176	999.586
1363.5191	-3	0.002989	31.0	27.0	25.29	25.489	0.0374	0.3522	1.1582	0.0048	0.0000	1365.072
1365.3493	0	0.003005	30.2	27.0	25.40	25.489	0.0354	0.3130	1.1560	0.0048	0.0000	1366.858
1363.5135	-2	0.002989	31.0	27.0	25.49	25.545	0.0375	0.3234	1.1493	0.0048	0.0022	1365.031
1365.3219	+1	0.003008	29.8	27.0	25.47	25.545	0.0355	0.3219	1.1575	0.0048	0.0022	1366.844
998.4528	+6	0.003467	26.0	26.0	25.42	25.566	0.0428	0.0899	-0.2922	-0.0009	-0.0191	998.273
999.7799	+6	0.003475	25.0	25.0	25.52	25.566	0.0408	0.0773	-0.2916	-0.0009	-0.0191	999.586
998.4345	+6	0.003467	26.0	26.0	25.29	25.562	0.0428	0.1079	-0.2935	-0.0009	-0.0011	998.290
999.7650	+10	0.003475	25.0	25.0	25.35	25.562	0.0408	0.0793	-0.2914	-0.0009	-0.0011	999.592
1363.4920	+1	0.002990	31.5	27.5	25.84	25.598	0.0375	0.3618	1.1562	0.0048	-0.0132	1365.039
1365.3095	0	0.003000	30.5	27.5	25.97	25.598	0.0354	0.3472	1.1599	0.0048	-0.0132	1366.844
1272.3167	+2	0.003098	30.0	27.0	25.84	25.594	0.0392	0.2527	0.7113	0.0028	0.0128	1273.336
1273.9934	-2	0.003096	29.0	27.0	25.89	25.594	0.0368	0.2590	0.7164	0.0028	0.0129	1275.021
1181.0813	-4	0.003201	28.7	27.0	26.00	25.681	0.0404	0.1969	0.3236	0.0012	-0.0092	1181.634
1182.6804	-4	0.003209	28.0	27.0	26.18	25.681	0.0383	0.1754	0.3242	0.0012	-0.0092	1183.210
1089.8038	-2	0.003322	27.0	27.0	26.03	25.644	0.0417	0.1347	-0.0118	-0.0001	-0.0125	1089.956
1091.2376	-1	0.003321	27.0	26.0	26.24	25.644	0.0394	0.1310	-0.0115	-0.0001	-0.0125	1091.384
1089.7902	-3	0.003323	27.0	26.0	25.91	25.636	0.0417	0.1410	-0.0109	-0.0001	-0.0110	1089.951
1091.2356	-1	0.003328	26.7	26.0	25.94	25.636	0.0395	0.1425	-0.0103	-0.0001	-0.0110	1091.396
1272.3197	-4	0.003096	30.0	26.0	25.65	25.477	0.0392	0.2733	0.7174	0.0028	-0.0128	1273.340
1274.0048	-3	0.003122	27.0	26.0	25.44	25.477	0.0375	0.2564	0.7221	0.0028	-0.0129	1275.011
1181.0987	0	0.003205	28.0	26.0	25.55	25.514	0.0405	0.1833	0.3267	0.0012	-0.0132	1181.637
1182.6769	-1	0.003226	26.0	25.0	25.26	25.514	0.0387	0.1678	0.3305	0.0012	-0.0132	1183.202
1363.4947	-2	0.002989	32.0	27.3	25.44	25.494	0.0373	0.3676	1.1607	0.0048	-0.0011	1365.064
1365.3399	-3	0.003007	29.7	26.5	25.35	25.494	0.0355	0.3084	1.1557	0.0048	-0.0011	1366.843
998.4290	-4	0.003466	26.0	26.0	25.25	25.468	0.0428	0.0976	-0.2920	-0.0009	0.0095	998.286
999.7610	-2	0.003475	25.0	25.0	25.16	25.468	0.0407	0.0678	-0.2895	-0.0009	0.0095	999.589
998.4381	-4	0.003467	26.0	26.0	25.19	25.460	0.0428	0.0896	-0.2910	-0.0009	-0.0004	998.278
999.7623	-2	0.003474	25.0	25.0	25.10	25.460	0.0407	0.0867	-0.2909	-0.0009	-0.0004	999.598
1363.5093	0	0.002993	31.5	27.0	25.52	25.435	0.0375	0.3572	1.1593	0.0048	-0.0044	1365.064
1365.3242	-1	0.003010	30.2	26.8	25.46	25.435	0.0355	0.3335	1.1622	0.0048	-0.0044	1366.856
1363.5019	-4	0.002998	31.5	27.0	25.29	25.460	0.0376	0.3525	1.1594	0.0048	-0.0103	1365.046
1365.3288	-2	0.003016	29.2	26.0	25.05	25.460	0.0357	0.3243	1.1625	0.0048	-0.0103	1366.846

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TABLE XI (Continued)

t_r / P_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
0	134	+0.0008	+0.0009	+0.0009	25.24	R	1003.3137	1.258	1.903	0.0492	0.0242	0.0370	0.0280
1000	3/26/36	+0.0009	+0.0010	+0.0000	25.490	G	1004.6330	1.171	1.726	0.0948	0.0229	0.0336	0.0281
0	135	-0.0005	-0.0004	-0.0009	25.30	R	1003.3082	1.239	1.818	0.0507	0.0239	0.0359	0.0281
1000	3/26/36	-0.0013	-0.0014	0.0004	25.494	G	1004.6375	1.236	1.559	0.0625	0.0239	0.0312	0.0282
0	136	+0.0013	+0.0013	+0.0012	25.74	R	753.4042	1.072	1.785	0.0867	0.0205	0.0355	0.0205
750	4/9/36	+0.0011	+0.0013	0.0001	25.464	G	754.9243	1.243	1.461	0.1167	0.0245	0.0297	0.0206
0	137	+0.0002	+0.0006	+0.0005	25.77	R	753.4000	1.054	1.771	0.0853	0.0202	0.0353	0.0206
750	4/9/36	+0.0003	+0.0008	0.0002	25.462	G	754.9135	1.209	1.583	0.1460	0.0239	0.0315	0.0206
100	138	100.0022	100.0038	100.0023	25.85	R	1028.6630	1.224	1.767	0.0828	0.0236	0.0352	0.0296
750	4/14/36	100.0016	100.0015	0.0008	25.513	G	1030.7708	1.137	1.453	0.0823	0.0226	0.0295	0.0297
100	139	100.0000	100.0008	99.9998	25.77	R	1028.6635	1.206	1.760	0.0540	0.0233	0.0351	0.0295
750	4/14/36	99.9993	99.9992	0.0006	25.469	G	1030.7642	1.075	1.630	0.0670	0.0215	0.0322	0.0295
0	140	-0.0014	-0.0010	-0.0012	25.37	R	753.4380	1.108	1.813	0.0620	0.0211	0.0359	0.0201
750	4/16/36	-0.0013	-0.0012	0.0001	25.398	G	754.9577	1.255	1.420	0.0843	0.0247	0.0290	0.0201
0	141	-0.0009	-0.0002	-0.0006	25.44	R	753.4280	1.114	1.882	0.1042	0.0212	0.0368	0.0202
750	4/16/36	-0.0010	-0.0004	0.0003	25.419	G	754.9578	1.238	1.501	0.1082	0.0244	0.0303	0.0202
100	142	99.9985	99.9989	99.9989	25.60	R	1028.6765	1.310	1.695	0.0595	0.0250	0.0342	0.0292
750	4/17/36	99.9991	99.9990	0.0002	25.425	G	1030.7697	1.126	1.455	0.0777	0.0224	0.0296	0.0293
100	143	99.9992	99.9992	99.9992	25.62	R	1028.6560	1.284	1.818	0.1138	0.0246	0.0359	0.0293
750	4/17/36	99.9993	99.9991	0.0000	25.434	G	1030.7595	1.121	1.657	0.0992	0.0223	0.0327	0.0293
0	144	-0.0003	0.0000	-0.0001	25.34	R	753.4342	1.096	1.769	0.0592	0.0209	0.0353	0.0201
750	4/18/36	-0.0002	0.0000	0.0001	25.452	G	754.9760	1.264	1.670	0.0560	0.0248	0.0328	0.0201
0	145	-0.0011	-0.0004	-0.0008	26.10	R	753.4363	1.177	1.842	0.0533	0.0222	0.0362	0.0209
750	4/20/36	-0.0011	-0.0005	0.0003	25.505	G	754.9707	1.318	1.522	0.0740	0.0257	0.0306	0.0210
100	146	100.0002	100.0006	99.9999	26.15	R	1028.6925	1.258	1.772	0.0553	0.0241	0.0353	0.0301
750	4/21/36	100.0000	99.9988	0.0006	25.493	G	1030.7842	1.111	1.408	0.0775	0.0222	0.0288	0.0301
75	147	74.9977	74.9980	74.9978	26.15	R	959.9347	1.223	1.705	0.0843	0.0235	0.0344	0.0275
750	4/23/36	74.9980	74.9973	0.0002	25.481	G	961.8925	1.084	1.493	0.0770	0.0211	0.0302	0.0276
50	148	50.0022	50.0044	50.0030	25.57	R	891.1673	1.166	1.734	0.0755	0.0223	0.0348	0.0237
750	4/25/36	50.0035	50.0019	0.0010	25.447	G	892.9962	1.107	1.277	0.0505	0.0211	0.0266	0.0237
25	149	24.9996	25.0012	25.0006	26.00	R	822.3282	1.138	1.747	0.0742	0.0217	0.0350	0.0225
750	4/28/36	25.0002	25.0012	0.0006	25.482	G	823.9990	1.105	1.306	0.0843	0.0216	0.0271	0.0225
25	150	24.9996	25.0011	25.0004	26.07	R	822.3257	1.146	1.755	0.0755	0.0218	0.0351	0.0226
750	4/28/36	25.0003	25.0008	0.0005	25.467	G	823.9888	1.086	1.625	0.0885	0.0213	0.0322	0.0226
75	151	74.9972	74.9984	74.9978	26.45	R	959.9548	1.233	1.713	0.0942	0.0237	0.0345	0.0279
750	4/29/36	74.9986	74.9972	0.0006	25.521	G	961.8980	1.105	1.431	0.0978	0.0214	0.0292	0.0280
50	152	50.0036	50.0044	50.0041	26.17	R	891.1867	1.197	1.740	0.0830	0.0228	0.0349	0.0245
750	4/29/36	50.0045	50.0040	0.0003	25.567	G	892.9872	1.127	1.382	0.1050	0.0214	0.0284	0.0245

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
998.4336	-5	0.003470	26.0	26.0	25.19	25.456	0.0428	0.0955	-0.2913	-0.0009	-0.0033	998.276
999.7487	-3	0.003480	25.0	25.0	25.10	25.456	0.0408	0.0974	-0.2915	-0.0009	-0.0033	999.591
998.4283	-5	0.003470	26.0	25.0	25.19	25.477	0.0429	0.0900	-0.2907	-0.0009	0.0033	998.273
999.7559	-4	0.003483	25.0	25.0	25.03	25.477	0.0408	0.0732	-0.2893	-0.0009	0.0033	999.583
749.7373	+1	0.003464	26.3	26.0	25.61	25.447	0.0321	0.0760	-0.2200	-0.0005	-0.0033	749.622
751.2598	+2	0.003478	25.5	26.0	25.58	25.447	0.0306	0.0637	-0.2192	-0.0005	-0.0033	751.131
749.7334	+2	0.003464	26.0	26.0	25.59	25.458	0.0321	0.0750	-0.2199	-0.0005	-0.0014	749.619
751.2470	+3	0.003478	26.0	26.0	25.53	25.458	0.0306	0.0788	-0.2206	-0.0005	-0.0014	751.134
1023.6577	-3	0.002990	32.0	28.0	25.71	25.479	0.0280	0.2542	0.8647	0.0027	-0.0063	1024.801
1025.7600	0	0.003002	30.2	27.2	25.49	25.479	0.0265	0.2272	0.8658	0.0027	-0.0063	1026.876
1023.6661	-3	0.002991	32.0	27.3	25.67	25.447	0.0281	0.2435	0.8629	0.0027	0.0006	1024.804
1025.7577	0	0.002999	30.0	27.0	25.56	25.447	0.0265	0.2367	0.8682	0.0027	0.0006	1026.892
749.7797	-2	0.003466	26.0	26.0	25.18	25.368	0.0321	0.0711	-0.2183	-0.0005	0.0033	749.667
751.3025	-1	0.003486	25.0	25.0	25.15	25.368	0.0307	0.0527	-0.2166	-0.0005	0.0033	751.172
749.7662	-2	0.003466	26.0	26.0	25.22	25.403	0.0321	0.0856	-0.2198	-0.0005	0.0017	749.665
751.2982	-1	0.003486	25.0	25.0	25.20	25.403	0.0307	0.0639	-0.2178	-0.0005	0.0017	751.176
1023.6895	-4	0.002988	30.0	27.0	25.49	25.405	0.0282	0.2403	0.8636	0.0027	0.0030	1024.827
1025.7746	-3	0.002989	29.2	27.0	25.33	25.405	0.0264	0.2255	0.8660	0.0027	0.0030	1026.898
1023.6654	-4	0.002989	30.5	27.0	25.49	25.424	0.0281	0.2689	0.8704	0.0027	0.0022	1024.838
1025.7596	-4	0.002991	29.0	26.5	25.17	25.424	0.0264	0.2497	0.8728	0.0027	0.0022	1026.913
749.7690	0	0.003459	26.0	26.0	25.28	25.437	0.0320	0.0680	-0.2189	-0.0005	0.0003	749.650
751.3096	+3	0.003477	26.0	26.0	25.52	25.437	0.0306	0.0611	-0.2190	-0.0005	0.0003	751.182
749.7651	-1	0.003462	27.0	26.0	25.97	25.502	0.0321	0.0705	-0.2207	-0.0005	0.0022	749.649
751.3011	+3	0.003478	26.0	26.0	25.97	25.502	0.0306	0.0568	-0.2196	-0.0005	0.0022	751.171
1023.6917	-2	0.002991	30.3	27.0	26.02	25.485	0.0283	0.2450	0.8623	0.0027	0.0003	1024.830
1025.7778	0	0.002990	30.5	27.7	25.87	25.485	0.0264	0.2216	0.8621	0.0027	0.0003	1026.891
955.2692	-2	0.003095	31.0	27.3	26.04	25.468	0.0293	0.1925	0.5343	0.0016	0.0061	956.033
957.2193	-1	0.003120	28.2	27.0	25.85	25.468	0.0280	0.1728	0.5373	0.0016	0.0061	957.965
886.8373	-2	0.003206	28.0	27.0	25.46	25.430	0.0304	0.1427	0.2462	0.0007	-0.0083	887.249
888.6643	-1	0.003224	28.0	26.7	25.33	25.430	0.0288	0.1006	0.2457	0.0007	-0.0083	889.032
818.3264	-4	0.003327	27.0	26.0	25.80	25.472	0.0314	0.1025	-0.0067	0.0000	-0.0017	818.452
819.9968	-2	0.003335	27.0	26.0	25.66	25.472	0.0297	0.0749	-0.0058	0.0000	-0.0017	820.094
818.3262	-4	0.003327	27.0	26.0	25.92	25.464	0.0314	0.1033	-0.0069	0.0000	-0.0011	818.453
819.9836	-2	0.003336	27.0	26.0	25.77	25.464	0.0297	0.0980	-0.0059	0.0000	-0.0011	820.104
955.2828	-4	0.003092	31.0	29.0	26.30	25.526	0.0292	0.1962	0.5328	0.0016	0.0061	956.049
957.2196	-1	0.003119	30.0	28.3	26.22	25.526	0.0279	0.1746	0.5352	0.0016	0.0061	957.965
886.8385	-1	0.003207	28.0	27.0	26.05	25.587	0.0305	0.1454	0.2438	0.0007	-0.0113	887.248
888.6353	0	0.003221	28.0	27.0	26.03	25.587	0.0289	0.1254	0.2447	0.0007	-0.0113	889.024

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TABLE XI (Continued)

t_r / p_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
100	153	100.0022	100.0021	100.0020	26.44	R	1028.7187	1.185	1.740	0.0922	0.0230	0.0349	0.0305
750	4/30/36	100.0020	100.0019	0.0001	25.510	G	1030.8102	1.074	1.357	0.1163	0.0215	0.0280	0.0306
0	154	+0.0020	+0.0024	+0.0025	25.74	R	753.4613	1.153	1.860	0.0527	0.0218	0.0365	0.0205
750	5/4/36	+0.0024	+0.0032	0.0004	25.510	G	754.9932	1.259	1.305	0.0637	0.0247	0.0271	0.0206
0	155	+0.0017	+0.0016	+0.0018	25.70	R	753.4528	1.185	1.771	0.1042	0.0224	0.0353	0.0205
750	5/4/36	+0.0017	+0.0024	0.0002	25.534	G	754.9897	1.283	1.247	0.1158	0.0251	0.0260	0.0205
100	156	100.0001	100.0016	100.0004	25.99	R	1028.7210	1.180	1.846	0.0728	0.0229	0.0363	0.0298
750	5/5/36	100.0005	99.9996	0.0006	25.593	G	1030.8285	1.099	1.230	0.0918	0.0220	0.0257	0.0299
100	157	100.0009	100.0020	100.0012	25.92	R	1028.7003	1.181	1.816	0.0967	0.0229	0.0359	0.0297
750	5/5/36	100.0009	100.0008	0.0004	25.553	G	1030.8015	1.118	1.528	0.1060	0.0223	0.0307	0.0298
0	158	-0.0008	-0.0008	-0.0007	26.07	R	753.4718	1.143	1.921	0.0600	0.0217	0.0373	0.0209
750	5/7/36	-0.0008	-0.0003	0.0002	25.622	G	754.9997	1.281	1.429	0.0652	0.0251	0.0292	0.0209
0	159	-0.0018	-0.0014	-0.0016	26.09	R	753.4677	1.081	1.854	0.0568	0.0207	0.0364	0.0209
750	5/7/36	-0.0016	-0.0014	0.0002	25.628	G	754.9957	1.182	1.676	0.0703	0.0234	0.0329	0.0210
150	160	149.9976	149.9948	149.9957	26.87	R	1166.1275	1.147	1.786	0.0945	0.0220	0.0355	0.0366
750	5/8/36	149.9946	149.9957	0.0010	25.693	G	1168.5112	1.023	1.533	0.1067	0.0210	0.0308	0.0367
150	161	149.9992	149.9971	149.9975	26.97	R	1166.1062	1.191	1.842	0.1518	0.0228	0.0362	0.0368
750	5/8/36	149.9975	149.9963	0.0008	25.710	G	1168.5318	1.099	1.465	0.1127	0.0224	0.0297	0.0369
0	162	-0.0006	+0.0001	-0.0003	25.97	R	753.4657	1.131	1.905	0.0980	0.0215	0.0371	0.0208
750	5/12/36	-0.0007	+0.0001	0.0004	25.631	G	755.0015	1.276	1.570	0.1088	0.0250	0.0314	0.0208
0	163	-0.0007	-0.0003	-0.0005	26.07	R	753.4762	1.028	1.778	0.0915	0.0198	0.0354	0.0209
750	5/12/36	-0.0008	-0.0002	0.0002	25.641	G	755.0157	1.170	1.467	0.0898	0.0232	0.0298	0.0209
100	164	100.0002	100.0011	100.0002	26.84	R	1028.7050	1.201	1.889	0.1507	0.0232	0.0369	0.0311
750	5/13/36	100.0000	99.9995	0.0004	25.680	G	1030.8207	1.098	1.416	0.1397	0.0219	0.0290	0.0312
100	165	100.0012	100.0022	100.0013	26.90	R	1028.7482	1.202	1.854	0.0852	0.0232	0.0364	0.0312
750	5/13/36	100.0012	100.0005	0.0005	25.706	G	1030.8520	1.059	1.247	0.1025	0.0212	0.0260	0.0313
0	166	-0.0011	-0.0007	-0.0007	26.17	R	753.4613	1.081	1.856	0.1438	0.0207	0.0364	0.0210
750	5/15/36	-0.0004	-0.0005	0.0002	25.613	G	754.9992	1.206	1.479	0.0867	0.0239	0.0300	0.0211
0	167	-0.0010	-0.0003	-0.0006	25.97	R	753.4568	1.117	1.923	0.1243	0.0213	0.0373	0.0208
750	5/15/36	-0.0004	-0.0005	0.0002	25.589	G	754.9900	1.218	1.651	0.1047	0.0241	0.326	0.0208
0	168	0.0000	+0.0006	+0.0002	27.14	R	451.8712	1.169	1.686	0.0892	0.0229	0.0341	0.0131
450	5/22/36	-0.0002	+0.0003	0.0003	27.556	G	452.7810	1.177	1.626	0.1118	0.0234	0.0322	0.0131
0	169	+0.0001	-0.0003	-0.0003	26.89	R	451.8637	1.208	1.714	0.0858	0.0236	0.0345	0.0129
450	5/22/36	-0.0007	-0.0002	0.0002	27.552	G	452.7795	1.241	1.652	0.0807	0.0245	0.0326	0.0129
100	170	100.0020	100.0011	100.0009	27.72	R	616.7887	1.155	1.610	0.0838	0.0221	0.0330	0.0165
450	5/23/36	99.9995	100.0010	0.0007	27.658	G	618.0420	1.091	1.232	0.0903	0.0222	0.0258	0.0166
100	171	100.0006	99.9988	99.9993	27.70	R	616.7892	1.207	1.677	0.0898	0.0230	0.0340	0.0165
450	5/23/36	99.9985	99.9993	0.0006	27.670	G	618.0463	1.173	1.563	0.0797	0.0236	0.0312	0.0166

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
1023.7143	-3	0.002991	33.0	31.0	26.35	25.509	0.0279	0.2555	0.8609	0.0027	-0.0055	1024.856
1025.8011	-2	0.003017	32.0	29.0	25.99	25.509	0.0266	0.2304	0.8647	0.0027	-0.0055	1026.920
749.7882	0	0.003491	26.0	26.0	25.61	25.481	0.0325	0.0713	-0.2187	-0.0005	-0.0069	749.666
751.3249	+3	0.003494	25.0	25.7	25.55	25.481	0.0308	0.0402	-0.2167	-0.0005	-0.0069	751.172
749.7782	0	0.003491	26.0	26.0	25.59	25.509	0.0324	0.0797	-0.2195	-0.0005	-0.0050	749.665
751.3196	+3	0.003494	25.0	26.0	25.62	25.509	0.0308	0.0496	-0.2178	-0.0005	-0.0050	751.177
1023.6990	-5	0.002983	32.0	29.0	25.83	25.581	0.0279	0.2565	0.8628	0.0027	-0.0011	1024.848
1025.8060	-1	0.002995	30.0	28.0	25.34	25.581	0.0264	0.2103	0.8602	0.0027	-0.0011	1026.904
1023.6862	-1	0.002983	31.5	29.0	25.81	25.535	0.0279	0.2630	0.8650	0.0027	-0.0033	1024.842
1025.7818	0	0.002997	30.0	28.0	25.39	25.535	0.0264	0.2418	0.8685	0.0027	-0.0033	1026.918
749.7829	-2	0.003489	26.0	26.0	25.92	25.625	0.0325	0.0763	-0.2205	-0.0005	+0.0019	749.673
751.3148	-1	0.003491	25.7	26.0	25.89	25.625	0.0308	0.0485	-0.2190	-0.0005	+0.0019	751.176
749.7779	0	0.003489	26.0	26.0	25.99	25.636	0.0325	0.0721	-0.2204	-0.0005	0.0044	749.666
751.3047	0	0.003493	26.0	26.0	26.02	25.636	0.0308	0.0649	-0.2207	-0.0005	0.0044	751.184
1160.4182	-101	0.002787	36.7	32.0	26.74	25.721	0.0248	0.3917	1.6280	0.0055	0.0118	1162.480
1162.7940	-97	0.002809	34.7	31.0	26.67	25.721	0.0236	0.3709	1.6347	0.0055	0.0119	1164.841
1160.3937	-99	0.002787	37.0	32.0	26.89	25.753	0.0248	0.4195	1.6383	0.0055	0.0069	1162.489
1162.8136	-95	0.002809	34.7	31.0	26.85	25.753	0.0236	0.3669	1.6319	0.0055	0.0069	1164.848
749.7755	-3	0.003496	26.0	26.0	25.90	25.632	0.0326	0.0852	-0.2210	-0.0005	0.0008	749.673
751.3129	+2	0.003489	26.0	26.0	26.01	25.632	0.0308	0.0685	-0.2211	-0.0005	0.0008	751.191
749.7847	-2	0.003496	26.0	26.0	25.96	25.644	0.0326	0.0767	-0.2205	-0.0005	0.0014	749.674
751.3256	+3	0.003489	26.0	26.0	26.04	25.644	0.0308	0.0574	-0.2202	-0.0005	0.0014	751.194
1023.6680	-3	0.002997	33.0	30.0	26.74	25.692	0.0281	0.2872	0.8666	0.0027	-0.0006	1024.852
1025.7800	+1	0.003002	31.0	29.0	26.70	25.692	0.0266	0.2440	0.8631	0.0027	-0.0006	1026.916
1023.7067	-2	0.002997	33.0	33.0	26.89	25.732	0.0282	0.2617	0.8594	0.0027	-0.0036	1024.855
1025.8086	+2	0.003000	31.0	29.0	26.89	25.732	0.0266	0.2160	0.8551	0.0027	-0.0036	1026.905
749.7737	-4	0.003496	26.0	26.7	26.06	25.598	0.0325	0.0944	-0.2221	-0.0005	0.0019	749.680
751.3137	+2	0.003487	26.0	26.0	26.20	25.598	0.0308	0.0573	-0.2203	-0.0005	0.0019	751.183
749.7720	-4	0.003495	26.0	26.0	25.87	25.583	0.0325	0.0929	-0.2214	-0.0005	0.0017	749.677
751.3051	+2	0.003487	25.5	26.0	25.75	25.583	0.0307	0.0723	-0.2207	-0.0005	0.0017	751.189
449.5002	-3	0.003491	27.0	28.0	27.14	27.532	0.0196	0.0430	-0.1397	-0.0002	-0.0003	449.423
450.4076	+2	0.003480	26.7	27.0	27.19	27.532	0.0185	0.0441	-0.1407	-0.0002	-0.0003	450.329
449.4931	+1	0.003492	27.0	27.0	26.87	27.528	0.0196	0.0436	-0.1393	-0.0002	0.0005	449.417
450.4069	+2	0.003482	26.0	27.0	26.95	27.528	0.0185	0.0402	-0.1400	-0.0002	0.0005	450.326
613.5440	-3	0.002984	34.0	31.0	27.68	27.636	0.0169	0.1460	0.4982	0.0009	-0.0015	614.204
614.7981	+1	0.002982	32.0	30.0	27.61	27.636	0.0159	0.1269	0.4974	0.0009	-0.0015	615.438
613.5431	-1	0.002986	34.0	31.0	27.70	27.655	0.0169	0.1506	0.4993	0.0009	0.0012	614.212
614.7970	+1	0.002981	32.0	30.0	27.61	27.655	0.0159	0.1422	0.5009	0.0009	0.0012	615.458

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TABLE XI (Continued)

t_r / P_o	Run No. / Date	$t_b(308)$ / $t_b(307)$	$t_b(107)$ / $t_b(310)$	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
0	172	-0.0011	-0.0016	-0.0018	28.12	R	451.8738	1.147	1.505	0.1107	0.0225	0.0314	0.0138
450	5/26/36	-0.0019	-0.0028	0.0005	27.695	G	452.7992	1.231	1.438	0.0868	0.0243	0.0293	0.0138
0	173	+0.0018	+0.0011	+0.0012	27.87	R	451.8810	1.184	1.626	0.0947	0.0232	0.0333	0.0136
450	5/26/36	+0.0008	+0.0010	0.0003	27.709	G	452.7918	1.259	1.634	0.1090	0.0248	0.0323	0.0136
100	174	100.0012	99.9991	100.0000	27.95	R	616.7692	1.227	1.680	0.1518	0.0233	0.0340	0.0167
450	5/27/36	99.9986	100.0009	0.0011	27.666	G	618.0260	1.144	1.396	0.1308	0.0231	0.0286	0.0168
75	175	74.9972	74.9958	74.9964	28.02	R	575.5858	1.186	1.640	0.1140	0.0228	0.0335	0.0155
450	5/27/36	74.9960	74.9968	0.0006	27.703	G	576.7652	1.133	1.437	0.0878	0.0228	0.0293	0.0156
50	176	50.0019	50.0016	50.0012	27.22	R	534.3563	1.170	1.547	0.1073	0.0227	0.0321	0.0144
450	5/28/36	50.0016	49.9997	0.0008	27.590	G	535.4483	1.141	1.590	0.0972	0.0229	0.317	0.0144
25	177	25.0019	25.0022	25.0021	27.65	R	493.1388	1.074	1.730	0.0815	0.0212	0.0347	0.0143
450	5/29/36	25.0020	25.0022	0.0001	27.604	G	494.1215	1.117	1.492	0.1178	0.0224	0.0302	0.0143
25	178	24.9986	24.9989	24.9988	27.59	R	493.1282	1.131	1.665	0.0792	0.0222	0.0338	0.0142
450	5/29/36	24.9987	24.9990	0.0002	27.613	G	494.1202	1.139	1.638	0.0985	0.0228	0.0324	0.0143
75	179	74.9985	74.9978	74.9980	28.17	R	575.5915	1.128	1.739	0.0833	0.0218	0.0348	0.0157
450	6/1/36	74.9970	74.9985	0.0006	27.666	G	576.7662	1.138	1.491	0.0950	0.0229	0.0302	0.0157
50	180	49.9992	49.9983	49.9988	27.87	R	534.3570	1.088	1.774	0.0985	0.0213	0.0353	0.0150
450	6/1/36	49.9977	50.0001	0.0008	27.680	G	535.4522	1.175	1.635	0.1035	0.0235	0.0323	0.0150
100	181	100.0024	100.0015	100.0016	28.19	R	616.7967	1.160	1.681	0.1090	0.0222	0.0340	0.0170
450	6/2/36	100.0006	100.0021	0.0006	27.736	G	618.0558	1.113	1.527	0.0963	0.0226	0.0307	0.0170
0	182	+0.0001	-0.0004	-0.0004	28.62	R	451.8898	1.221	1.670	0.1072	0.0238	0.0339	0.0141
450	6/3/36	-0.0008	-0.0006	0.0003	27.840	G	452.8023	1.240	1.662	0.1080	0.0245	0.0327	0.0141
0	183	+0.0015	+0.0014	+0.0011	28.84	R	451.8950	1.242	1.902	0.1033	0.0241	0.0370	0.0142
450	6/3/36	+0.0012	+0.0004	0.0004	27.871	G	452.8028	1.266	1.678	0.1055	0.0249	0.0330	0.0143
150	184	150.0020	149.9906	149.9951	29.59	R	699.1132	1.267	1.710	0.0870	0.0237	0.0344	0.0233
450	6/4/36	149.9895	149.9984	0.0051	27.926	G	700.5278	1.181	1.676	0.0917	0.0239	0.0329	0.0234
150	185	150.0021	149.9937	149.9968	29.75	R	699.1200	1.311	1.795	0.0833	0.0244	0.0356	0.0235
450	6/4/36	149.9929	149.9986	0.0035	27.909	G	700.5235	1.195	1.704	0.1003	0.0241	0.0334	0.0235
0	186	-0.0020	-0.0032	-0.0027	28.72	R	451.8888	1.175	1.856	0.0692	0.0230	0.0364	0.0142
450	6/6/36	-0.0029	-0.0027	0.0004	27.811	G	452.7883	1.274	1.806	0.0860	0.0251	0.0347	0.0142
0	187	+0.0007	-0.0004	0.0000	28.04	R	451.8812	1.194	1.762	0.0987	0.0233	0.0352	0.0137
450	6/6/36	-0.0007	+0.0003	0.0005	27.726	G	452.7862	1.301	1.784	0.0772	0.0255	0.0344	0.0137
100	188		100.0048	100.0046	28.70	R	616.8147	1.145	1.869	0.0612	0.0219	0.0366	0.0174
450	6/8/36	100.0035	100.0055	0.0007	27.845	G	618.0508	1.130	1.700	0.0540	0.0229	0.0333	0.0175
100	189		100.0038	100.0033	28.74	R	616.8087	1.173	1.692	0.0790	0.0224	0.0342	0.0175
450	6/8/36	100.0020	100.0040	0.0008	27.836	G	618.0623	1.178	1.784	0.0793	0.0237	0.0344	0.0175
0	190	+0.0002	+0.0006	+0.0004	27.29	R	451.8677	1.189	1.844	0.0637	0.0233	0.0363	0.0132
450	6/10/36	+0.0002	+0.0004	0.0002	27.598	G	452.7700	1.270	1.747	0.1032	0.0250	0.0339	0.0132

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
449.4944	-2	0.003492	28.0	28.0	28.12	27.682	0.0196	0.0397	-0.1410	-0.0002	0.0030	449.416
450.4188	-3	0.003479	28.0	28.0	28.30	27.682	0.0185	0.0332	-0.1415	-0.0002	0.0030	450.332
449.4991	-1	0.003489	28.0	28.0	27.79	27.703	0.0196	0.0418	-0.1409	-0.0002	-0.0020	449.417
450.4076	-2	0.003479	27.2	28.0	27.65	27.703	0.0185	0.0438	-0.1419	-0.0002	-0.0020	450.326
613.5241	0	0.002992	32.5	31.0	27.88	27.657	0.0170	0.1639	0.5026	0.0009	0.0000	614.208
614.7796	0	0.002992	31.0	29.0	27.58	27.657	0.0160	0.1442	0.5022	0.0009	0.0000	615.443
572.5528	-2	0.003093	31.5	30.0	27.89	27.698	0.0177	0.1191	0.3051	0.0005	0.0059	573.001
573.7302	-1	0.003094	30.0	29.0	27.75	27.698	0.0167	0.1038	0.3053	0.0005	0.0059	574.162
531.5519	0	0.003212	28.8	28.0	27.08	27.569	0.0184	0.0842	0.1353	0.0002	-0.0020	531.788
532.6388	0	0.003208	28.0	28.0	27.11	27.569	0.0174	0.0837	0.1358	0.0002	-0.0020	532.874
490.5457	-2	0.003333	29.0	28.0	27.55	27.586	0.0190	0.0627	-0.0147	0.0000	-0.0035	490.609
491.5289	-3	0.003330	28.0	28.0	27.42	27.586	0.0179	0.0589	-0.0146	0.0000	-0.0035	491.588
490.5362	-2	0.003333	28.0	28.0	27.50	27.602	0.0190	0.0598	-0.0146	0.0000	0.0020	490.602
491.5250	-2	0.003330	28.0	28.0	27.37	27.602	0.0179	0.0615	-0.0146	0.0000	0.0020	491.592
572.5602	-2	0.003092	32.3	30.0	28.07	27.653	0.0177	0.1175	0.3046	0.0005	0.0033	573.004
573.7344	-2	0.003095	30.0	29.0	28.05	27.653	0.0168	0.1078	0.3057	0.0005	0.0033	574.168
531.5400	-2	0.003247	28.0	28.0	27.80	27.672	0.0188	0.0921	0.1356	0.0002	0.0020	531.789
532.6346	-3	0.003245	28.0	28.0	27.82	27.672	0.0177	0.0866	0.1357	0.0002	0.0020	532.877
613.5429	-2	0.002977	33.8	31.0	28.13	27.734	0.0168	0.1548	0.4986	0.0009	-0.0026	614.211
614.7990	-1	0.002984	33.0	31.0	28.55	27.734	0.0159	0.1438	0.4989	0.0009	-0.0026	615.456
449.4977	-3	0.003474	29.0	29.0	28.59	27.843	0.0195	0.0452	-0.1432	-0.0002	0.0007	449.420
450.4072	-2	0.003463	29.0	29.0	28.83	27.843	0.0184	0.0446	-0.1442	-0.0002	0.0007	450.326
449.4976	0	0.003480	29.0	29.0	28.84	27.879	0.0195	0.0525	-0.1441	-0.0002	-0.0018	449.424
450.4055	-1	0.003470	29.0	29.0	29.11	27.879	0.0185	0.0449	-0.1444	-0.0002	-0.0018	450.322
695.4079	-2	0.002875	31.0	30.0	29.56	27.963	0.0167	0.2350	0.9560	0.0019	0.0081	696.626
696.8168	-1	0.002873	31.0	30.0	29.69	27.963	0.0155	0.2332	0.9607	0.0019	0.0081	698.036
695.4165	-1	0.002880	31.0	30.0	29.68	27.946	0.0167	0.2386	0.9576	0.0019	0.0053	696.637
696.8144	+1	0.002867	31.0	30.0	29.74	27.946	0.0155	0.2368	0.9619	0.0019	0.0053	698.036
449.4958	-2	0.003487	28.0	28.3	28.61	27.812	0.0196	0.0457	-0.1426	-0.0002	0.0044	449.423
450.3944	+1	0.003475	28.0	28.3	28.49	27.812	0.0185	0.0463	-0.1435	-0.0002	0.0045	450.320
449.4962	-2	0.003487	28.0	28.0	27.99	27.726	0.0196	0.0471	-0.1418	-0.0002	0.0000	449.421
450.3994	+1	0.003480	27.0	28.0	27.86	27.726	0.0185	0.0442	-0.1422	-0.0002	0.0000	450.320
613.5462	-1	0.002994	33.2	31.0	28.63	27.857	0.0171	0.1534	0.4974	0.0009	-0.0076	614.207
614.7801	+1	0.003003	31.3	29.7	28.27	27.857	0.0162	0.1436	0.4999	0.0009	-0.0076	615.433
613.5442	0	0.002988	33.0	31.3	28.65	27.845	0.0171	0.1492	0.4961	0.0009	-0.0054	614.202
614.7923	+1	0.002996	32.0	30.0	28.65	27.845	0.0161	0.1527	0.5010	0.0009	-0.0054	615.458
449.4916	0	0.003496	27.0	27.7	27.21	27.577	0.0196	0.0445	-0.1399	-0.0002	-0.0007	449.415
450.3932	-1	0.003489	26.0	27.0	27.09	27.577	0.0186	0.0469	-0.1408	-0.0002	-0.0007	450.317

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TABLE XI (Continued)

t_r / p_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_s / t_{H_2}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
0	191	+0.0018	+0.0016	+0.0015	27.37	R	451.8645	1.213	1.750	0.1087	0.0237	0.0350	0.0132
450	6/10/36	+0.0013	+0.0013	0.0002	27.628	G	452.7772	1.287	1.728	0.1073	0.0253	0.0337	0.0133
150	192	150.0066	149.9995	150.0018	27.77	R	699.0770	1.253	1.817	0.0740	0.0235	0.0359	0.0214
450	6/11/36	149.9979	150.0030	0.0030	27.627	G	700.5048	1.187	1.784	0.0678	0.0240	0.0344	0.0215
150	193	150.0106	150.0050	150.0068	27.99	R	699.0868	1.300	1.749	0.1180	0.0242	0.0350	0.0216
450	6/11/36	150.0028	150.0086	0.0028	27.691	G	700.5072	1.181	1.809	0.0790	0.0239	0.0347	0.0217
0	194	+0.0004	-0.0003	-0.0001	27.84	R	451.8870	1.221	1.776	0.0790	0.0238	0.0354	0.0136
450	6/13/36	-0.0006	+0.0002	0.0004	27.688	G	452.7942	1.245	1.815	0.0832	0.0246	0.0348	0.0136
0	195	-0.0002	0.0000	-0.0002	27.62	R	451.8763	1.239	1.729	0.1002	0.0241	0.0347	0.0134
450	6/13/36	-0.0003	-0.0001	0.0001	27.675	G	452.7818	1.275	1.793	0.1132	0.0251	0.0345	0.0134
100	196	100.0024	100.0011	100.0017	27.52	R	616.7838	1.152	1.741	0.1025	0.0220	0.0349	0.0163
450	6/15/36	100.0005	100.0029	0.0009	27.635	G	618.0325	1.151	1.792	0.0837	0.0232	0.0345	0.0164
100	197	100.0034	100.0078	100.0052	27.47	R	616.7795	1.174	1.720	0.1067	0.0224	0.0346	0.0163
450	6/15/36	100.0038	100.0056	0.0016	27.634	G	618.0278	1.164	1.813	0.0805	0.0235	0.0348	0.0164
0	198	-0.0002	+0.0005	-0.0001	27.10	R	451.8780	1.248	1.851	0.0872	0.0242	0.0364	0.0131
450	6/17/36	-0.0003	-0.0005	0.0003	27.618	G	452.7800	1.272	1.808	0.0940	0.0250	0.0347	0.0131
0	199	-0.0012	+0.0022	-0.0002	27.50	R	451.8778	1.261	1.770	0.0688	0.0245	0.0353	0.0133
450	6/17/36	-0.0011	-0.0006	0.0012	27.615	G	452.7788	1.304	1.862	0.0728	0.0256	0.0353	0.0134
0	200	-0.0001	-0.0002	0.0000	29.30	R	603.0902	1.160	1.906	0.1210	0.0222	0.0371	0.0172
600	6/27/36	+0.0004	-0.0002	0.0002	29.697	G	603.7143	1.218	1.548	0.0903	0.0244	0.0310	0.0172
0	201	-0.0008	-0.0004	-0.0006	29.29	R	603.0957	1.153	1.849	0.1042	0.0221	0.0363	0.0171
600	6/27/36	-0.0003	-0.0007	0.0002	29.698	G	603.7042	1.225	1.455	0.1103	0.0245	0.0296	0.0172
100	202	100.0010	99.9992	100.0003	29.45	R	823.2892	1.171	1.848	0.0953	0.0222	0.0363	0.0268
600	6/29/36	100.0021	99.9988	0.0013	29.658	G	824.1442	1.218	1.689	0.0765	0.0235	0.0331	0.0268
100	203	100.0009	99.9986	100.0000	29.62	R	823.2855	1.146	1.911	0.0990	0.0218	0.0371	0.0270
600	6/29/36	100.0018	99.9986	0.0014	29.657	G	824.1362	1.176	1.741	0.0895	0.0228	0.0338	0.0270
0	204	-0.0012	-0.0018	-0.0012	29.17	R	603.0923	1.068	1.823	0.0765	0.0206	0.0360	0.0170
600	6/30/36	-0.0005	-0.0015	0.0004	29.656	G	603.6970	1.091	1.586	0.1128	0.0221	0.0316	0.0171
0	205	-0.0003	-0.0002	-0.0002	29.19	R	603.0935	1.192	1.841	0.0858	0.0228	0.0362	0.0171
600	6/30/36	-0.0002	-0.0003	0.0000	29.648	G	603.7060	1.228	1.855	0.0835	0.0246	0.0353	0.0171
150	206	150.0023	149.9961	149.9991	29.25	R	933.2023	1.264	1.883	0.0622	0.0241	0.0368	0.0306
600	7/1/36	150.0021	149.9960	0.0031	29.645	G	934.1498	1.167	1.760	0.0953	0.0222	0.0341	0.0306
150	207	150.0024	149.9970	149.9999	29.40	R	933.1872	1.186	1.808	0.1072	0.0228	0.0358	0.0308
600	7/1/36	150.0030	149.9973	0.0028	29.646	G	934.1627	1.121	1.840	0.0830	0.0215	0.0351	0.0308
0	208	-0.0003	-0.0003	-0.0002	29.12	R	603.0913	1.136	1.898	0.0780	0.0218	0.0370	0.0170
600	7/3/36	0.0000	-0.0001	0.0001	29.680	G	603.7028	1.178	1.804	0.0943	0.0237	0.0346	0.0170
0	209	+0.0012	+0.0016	+0.0014	29.17	R	603.1038	1.220	1.813	0.1003	0.0232	0.0359	0.0170
600	7/3/36	+0.0013	+0.0014	0.0001	29.685	G	603.7188	1.286	1.850	0.0788	0.0256	0.0352	0.0171

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
449.4877	-3	0.003491	27.0	28.0	27.24	27.615	0.0196	0.0482	-0.1405	-0.0002	-0.0025	449.412
450.3985	+1	0.003484	27.0	27.0	27.12	27.615	0.0185	0.0469	-0.1411	-0.0002	-0.0025	450.320
695.4060	0	0.002861	29.0	28.0	27.67	27.607	0.0164	0.2375	0.9649	0.0019	-0.0030	696.624
696.8283	-2	0.002853	29.0	28.0	27.54	27.607	0.0152	0.2331	0.9684	0.0019	-0.0030	698.044
695.4094	0	0.002860	29.0	28.0	27.84	27.682	0.0164	0.2445	0.9667	0.0019	-0.0112	696.628
696.8224	-2	0.002856	29.0	28.0	27.69	27.682	0.0153	0.2370	0.9692	0.0019	-0.0112	698.035
449.5053	-3	0.003489	27.0	28.0	27.71	27.676	0.0196	0.0445	-0.1410	-0.0002	0.0002	449.428
450.4091	-2	0.003482	27.0	27.0	27.55	27.676	0.0185	0.0460	-0.1417	-0.0002	0.0002	450.332
449.4965	-2	0.003490	27.0	28.0	27.49	27.666	0.0196	0.0462	-0.1408	-0.0002	0.0003	449.422
450.3984	-1	0.003482	27.0	27.2	27.31	27.666	0.0185	0.0499	-0.1418	-0.0002	0.0003	450.325
613.5395	-1	0.002999	33.0	30.0	27.45	27.615	0.0171	0.1563	0.5024	0.0009	-0.0028	614.213
614.7833	-2	0.003007	30.0	29.0	27.09	27.615	0.0162	0.1538	0.5064	0.0009	-0.0028	615.458
613.5360	-4	0.002999	32.5	30.0	27.41	27.617	0.0171	0.1561	0.5026	0.0009	-0.0086	614.204
614.7787	-1	0.003007	30.0	28.3	27.03	27.617	0.0162	0.1541	0.5068	0.0009	-0.0086	615.448
449.5009	-4	0.003497	27.0	27.0	27.05	27.602	0.0196	0.0482	-0.1400	-0.0002	0.0002	449.429
450.4006	-3	0.003490	26.5	27.0	27.32	27.602	0.0186	0.0474	-0.1412	-0.0002	0.0002	450.325
449.5025	-3	0.003493	27.0	28.0	27.45	27.607	0.0196	0.0427	-0.1402	-0.0002	0.0003	449.425
450.4000	0	0.003485	27.0	27.0	27.66	27.607	0.0186	0.0460	-0.1415	-0.0002	0.0003	450.323
599.6930	-1	0.003476	29.0	29.0	29.31	29.673	0.0262	0.0735	-0.2010	-0.0004	0.0000	599.591
600.3218	0	0.003477	28.5	29.0	28.96	29.673	0.0248	0.0503	-0.1992	-0.0004	0.0000	600.197
599.6989	-1	0.003476	29.0	29.0	29.29	29.678	0.0262	0.0676	-0.2004	-0.0004	0.0013	599.593
600.3131	0	0.003477	28.5	29.0	28.98	29.678	0.0248	0.0497	-0.1992	-0.0004	0.0013	600.189
818.6669	-5	0.002958	35.3	32.5	29.47	29.633	0.0224	0.2124	0.6463	0.0016	-0.0007	819.549
819.5215	-2	0.002966	34.0	32.0	29.31	29.633	0.0211	0.1962	0.6473	0.0016	-0.0007	820.387
818.6623	-5	0.003002	30.0	31.0	29.59	29.637	0.0233	0.2170	0.6514	0.0016	0.0000	819.556
819.5125	-2	0.002994	30.0	31.0	29.32	29.637	0.0217	0.2031	0.6513	0.0016	0.0000	820.390
599.6988	0	0.003476	29.0	29.3	29.19	29.631	0.0262	0.0608	-0.1995	-0.0004	0.0026	599.588
600.3061	+1	0.003476	29.0	29.0	29.15	29.631	0.0248	0.0567	-0.1999	-0.0004	0.0026	600.190
599.7030	+1	0.003476	29.0	30.0	29.16	29.629	0.0261	0.0636	-0.1998	-0.0004	0.0004	599.593
600.3147	+2	0.003476	29.0	29.0	29.03	29.629	0.0248	0.0630	-0.2004	-0.0004	0.0004	600.202
927.9685	+1	0.002841	30.8	30.0	29.26	29.604	0.0218	0.3170	1.2592	0.0033	0.0020	929.572
928.9115	0	0.002834	31.0	30.0	29.03	29.604	0.0202	0.3173	1.2653	0.0034	0.0020	930.520
927.9532	+2	0.002833	31.0	30.2	29.39	29.612	0.0217	0.3264	1.2616	0.0033	0.0002	929.566
928.9227	+1	0.002825	31.0	30.3	29.22	29.612	0.0201	0.3188	1.2645	0.0034	0.0002	930.530
599.6954	-2	0.003478	29.0	29.0	29.09	29.659	0.0262	0.0643	-0.1997	-0.0004	0.0004	599.586
600.3077	-3	0.003477	29.0	29.0	29.01	29.659	0.0248	0.0628	-0.2004	-0.0004	0.0004	600.195
599.7098	-2	0.003474	29.0	29.0	29.12	29.671	0.0261	0.0652	-0.2000	-0.0004	-0.0031	599.598
600.3245	-3	0.003476	29.0	29.0	29.08	29.671	0.0248	0.0616	-0.2005	-0.0004	-0.0031	600.207

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TABLE XI (Continued)

t_r / P_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
100	210	100.0028	100.0013	100.0023	29.29	R	823.3158	1.110	1.918	0.1047	0.0212	0.0372	0.0266
600	7/6/36	100.0044	100.0006	0.0013	29.683	G	824.1652	1.106	1.773	0.1098	0.0216	0.0342	0.0266
100	211	100.0016	100.0001	100.0011	29.07	R	823.3060	1.206	1.828	0.0850	0.0228	0.0361	0.0263
600	7/6/36	100.0030	99.9996	0.0012	29.670	G	824.1620	1.204	1.846	0.0848	0.0232	0.0352	0.0263
0	212	-0.0002	0.0000	0.0000	30.07	R	603.1117	1.158	1.931	0.0705	0.0222	0.0374	0.0179
600	7/8/36	-0.0001	+0.0001	0.0001	29.791	G	603.7107	1.185	1.766	0.1422	0.0238	0.0342	0.0179
0	213	-0.0010	-0.0008	-0.0008	30.34	R	603.1045	1.186	1.845	0.1242	0.0227	0.0363	0.0181
600	7/8/36	-0.0006	-0.0007	0.0001	29.828	G	603.7278	1.238	1.818	0.0838	0.0247	0.0346	0.0181
150	214	150.0112	150.0071	150.0088	30.75	R	933.2537	1.201	1.824	0.1117	0.0230	0.0360	0.0327
600	7/9/36	150.0108	150.0062	0.0022	29.891	G	934.2202	1.152	1.466	0.1090	0.0220	0.0298	0.0327
150	215	150.0025	149.9980	149.9998	31.05	R	933.2372	1.082	1.908	0.1108	0.0210	0.0371	0.0331
600	7/10/36	150.0025	149.9962	0.0027	29.868	G	934.1942	1.064	1.661	0.1022	0.0205	0.0327	0.0331
100	216	99.9977	99.9976	99.9975	30.87	R	823.3142	1.142	1.841	0.1232	0.0217	0.0362	0.0285
600	7/10/36	99.9987	99.9961	0.0007	29.910	G	824.1772	1.184	1.536	0.1048	0.0229	0.0308	0.0285
		t_b(308) / t_b(307)	t_b(306) / t_b(310)										
100	217	99.9993	99.9991	99.9991	29.95	R	823.3117	1.100	1.917	0.0713	0.0210	0.0372	0.0274
600	7/11/36	100.0007	99.9973	0.0009	29.749	G	824.1515	1.116	1.761	0.0998	0.0218	0.0341	0.0274
150	218	150.0040	149.9992	150.0012	29.07	R	933.2163	1.098	1.898	0.1045	0.0213	0.0370	0.0303
600	7/13	150.0042	149.9972	0.0030	29.654	G	934.1690	1.065	1.834	0.0882	0.0205	0.0350	0.0303
150	219	150.0026	149.9993	150.0014	29.40	R	933.2157	1.140	1.865	0.0978	0.0220	0.0365	0.0308
600	7/13/36	150.0052	149.9984	0.0025	29.678	G	934.1762	1.158	1.853	0.0835	0.0221	0.0352	0.0308
0	220	+0.0006	+0.0011	+0.0008	29.54	R	603.1038	1.162	1.843	0.1128	0.0222	0.0363	0.0174
600	7/15/36	+0.0007	+0.0007	0.0002	29.716	G	603.7190	1.245	1.595	0.1393	0.0249	0.0317	0.0174
0	221	-0.0016	-0.0012	-0.0014	29.60	R	603.1018	1.213	1.898	0.0888	0.0231	0.0370	0.0174
600	7/15/36	-0.0012	-0.0016	0.0002	29.691	G	603.7227	1.280	1.666	0.0840	0.0255	0.0328	0.0175
100	222	99.9932	99.9927	99.9935	30.22	R	823.3080	1.150	1.870	0.0822	0.0219	0.0366	0.0277
600	7/16/36	99.9958	99.9923	0.0012	29.771	G	824.1587	1.144	1.633	0.0840	0.0222	0.0323	0.0277
100	223	99.9925	99.9920	99.9926	30.29	R	823.3020	1.192	1.869	0.0990	0.0225	0.0366	0.0278
600	7/16/36	99.9947	99.9914	0.0010	29.779	G	824.1515	1.228	1.705	0.1085	0.0236	0.0334	0.0278
0	224	-0.0002	+0.0001	+0.0001	29.37	R	603.1112	1.199	1.832	0.0598	0.0229	0.0361	0.0172
600	7/24/36	+0.0013	-0.0008	0.0006	29.732	G	603.7153	1.200	1.810	0.1058	0.0241	0.0347	0.0173
0	225	-0.0006	0.0000	-0.0003	29.47	R	603.1010	1.191	1.711	0.1178	0.0227	0.0345	0.0173
600	7/24/36	-0.0003	-0.0002	0.0002	29.734	G	603.7177	1.265	1.648	0.1220	0.0252	0.0325	0.0173
0	226	-0.0020	-0.0019	-0.0020	29.89	R	335.0465	1.248	1.805	0.1222	0.0250	0.0358	0.0096
333	7/31/36	-0.0023	-0.0018	0.0002	29.781	G	336.0598	1.404	1.741	0.0390	0.0272	0.0338	0.0097
0	227	-0.0015	-0.0012	-0.0014	29.52	R	335.0535	1.313	1.638	0.1010	0.0261	0.0334	0.0094
333	7/31/36	-0.0014	-0.0015	0.0001	29.787	G	336.0387	1.426	1.661	0.1365	0.0275	0.0327	0.0094

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
818.6875	-5	0.002993	34.0	32.8	29.34	29.648	0.0229	0.2190	0.6504	0.0016	-0.0051	819.576
819.5355	-3	0.002988	34.0	32.0	29.03	29.648	0.0214	0.2106	0.6523	0.0016	-0.0051	820.416
818.6821	-4	0.002990	34.0	32.0	29.15	29.633	0.0229	0.2083	0.6486	0.0016	-0.0024	819.561
819.5346	-2	0.002988	34.0	31.8	29.22	29.633	0.0214	0.2080	0.6515	0.0016	-0.0024	820.415
599.7045	-1	0.003473	30.0	30.0	30.12	29.784	0.0262	0.0642	-0.2021	-0.0004	0.0000	599.592
600.3049	0	0.003472	30.0	30.0	30.08	29.784	0.0247	0.0711	-0.2035	-0.0004	0.0000	600.197
599.6951	+1	0.003467	30.0	31.0	30.36	29.830	0.0261	0.0717	-0.2038	-0.0004	0.0018	599.590
600.3184	0	0.003466	30.0	30.0	30.40	29.830	0.0247	0.0615	-0.2034	-0.0004	0.0018	600.203
927.9801	+1	0.002866	31.0	30.7	30.77	29.913	0.0224	0.3290	1.2575	0.0033	-0.0194	929.573
928.9463	-1	0.002842	31.0	31.0	30.48	29.913	0.0205	0.2999	1.2511	0.0033	-0.0194	930.502
927.9648	+1	0.002863	31.0	31.0	31.11	29.881	0.0224	0.3342	1.2583	0.0033	0.0004	929.583
928.9203	-1	0.002834	31.0	31.0	31.00	29.881	0.0205	0.3124	1.2542	0.0033	0.0004	930.511
818.6557	-5	0.003017	31.0	31.0	30.75	29.930	0.0237	0.2198	0.6475	0.0016	0.0055	819.554
819.5203	-3	0.002999	31.0	31.0	30.36	29.930	0.0219	0.1941	0.6445	0.0016	0.0055	820.388
818.6743	-1	0.003034	30.0	30.0	29.83	29.730	0.0239	0.2098	0.6507	0.0016	0.0020	819.562
819.5132	-1	0.003013	30.0	30.0	29.55	29.730	0.0221	0.2072	0.6523	0.0016	0.0020	820.398
927.9776	0	0.002870	29.3	29.0	29.02	29.602	0.0224	0.3314	1.2690	0.0034	-0.0026	929.601
928.9262	0	0.002850	30.0	30.0	28.78	29.602	0.0204	0.3201	1.2685	0.0034	-0.0026	930.536
927.9747	+1	0.002852	30.0	30.0	29.40	29.637	0.0221	0.3272	1.2636	0.0033	-0.0031	929.588
928.9312	-1	0.002847	30.0	30.0	29.15	29.637	0.0204	0.3197	1.2667	0.0034	-0.0031	930.538
599.7054	-2	0.003441	30.0	30.0	29.55	29.705	0.0258	0.0691	-0.2025	-0.0004	-0.0018	599.596
600.3244	-2	0.003453	29.0	29.3	29.28	29.705	0.0246	0.0624	-0.2017	-0.0004	-0.0018	600.208
599.7063	-4	0.003438	30.0	30.0	29.58	29.680	0.0258	0.0664	-0.2023	-0.0004	0.0031	599.599
600.3304	-3	0.003449	29.0	29.7	29.31	29.680	0.0245	0.0545	-0.2011	-0.0004	0.0031	600.211
818.6691	+3	0.003001	32.2	31.0	30.27	29.758	0.0233	0.2104	0.6465	0.0016	0.0143	819.565
819.5196	+3	0.002998	31.0	31.0	30.13	29.758	0.0219	0.1950	0.6465	0.0016	0.0143	820.399
818.6626	-6	0.003015	30.8	30.8	30.23	29.776	0.0236	0.2146	0.6487	0.0016	0.0163	819.567
819.5116	-5	0.003010	30.8	31.0	30.03	29.776	0.0220	0.2059	0.6499	0.0016	0.0163	820.407
599.7117	-2	0.003436	30.0	29.0	29.32	29.718	0.0258	0.0577	-0.2011	-0.0004	-0.0002	599.594
600.3151	0	0.003444	29.0	29.0	29.12	29.718	0.0245	0.0656	-0.2021	-0.0004	-0.0002	600.202
599.7029	0	0.003432	30.0	30.0	29.42	29.722	0.0257	0.0643	-0.2022	-0.0004	0.0007	599.591
600.3206	+1	0.003441	29.0	29.0	29.28	29.722	0.0245	0.0615	-0.2020	-0.0004	0.0007	600.205
333.1516	+1	0.003438	30.0	30.0	29.77	29.776	0.0143	0.0389	-0.1129	-0.0001	0.0024	333.094
334.1635	-2	0.003447	30.0	30.0	29.68	29.776	0.0136	0.0275	-0.1122	-0.0001	0.0024	334.095
333.1615	+1	0.003431	30.0	30.0	29.36	29.784	0.0143	0.0322	-0.1121	-0.0001	0.0017	333.098
334.1432	-1	0.003443	29.3	29.2	29.05	29.784	0.0136	0.0365	-0.1126	-0.0001	0.0017	334.082

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TABLE XI (Continued)

t_r P_o	Run No. Date	t_b(308) t_b(307)	t_b(306) t_b(310)	t_b(ave.) Ave. dev.	t_s t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
100	228	100.0018	100.0010	100.0014	30.22	R	457.2808	1.128	1.867	0.1357	0.0222	0.0366	0.0153
333	8/5/36	100.0001	100.0029	0.0009	29.864	G	458.6567	1.184	1.710	0.0605	0.0235	0.0334	0.0154
100	229	100.0018	100.0010	100.0016	30.37	R	457.2837	1.174	1.650	0.0995	0.0230	0.0336	0.0154
333	8/5/36	100.0004	100.0030	0.0008	29.812	G	458.6432	1.200	1.697	0.0938	0.0238	0.0333	0.0155
0	230	+0.0014	+0.0018	+0.0016	29.75	R	335.0492	1.181	1.852	0.1307	0.0239	0.0364	0.0095
333	8/8/36	+0.0017	+0.0017	0.0002	29.771	G	336.0478	1.368	1.728	0.1067	0.0266	0.0337	0.0096
0	231	-0.0008	-0.0003	-0.0005	29.49	R	335.0600	1.291	1.696	0.1010	0.0258	0.0342	0.0094
333	8/8/36	-0.0004	-0.0005	0.0002	29.747	G	336.0543	1.392	1.730	0.0800	0.0270	0.0337	0.0094
150	232	150.0054	149.9978	150.0016	30.07	R	518.2923	1.178	1.868	0.0838	0.0229	0.0366	0.0165
333	8/10/36	150.0008	150.0025	0.0023	29.745	G	519.8352	1.279	1.764	0.0927	0.0253	0.0341	0.0165
150	233	150.0041	149.9977	150.0006	30.37	R	518.2913	1.223	1.877	0.1057	0.0237	0.0367	0.0167
333	8/10/36	149.9994	150.0011	0.0020	29.794	G	519.8335	1.249	1.788	0.0927	0.0248	0.0344	0.0168
0	234	+0.0003	+0.0007	+0.0005	29.77	R	335.0595	1.252	1.926	0.0980	0.0251	0.0373	0.0095
333	8/12/36	+0.0008	+0.0002	0.0002	29.757	G	336.0417	1.363	1.816	0.1575	0.0265	0.0348	0.0096
0	235	-0.0006	0.0000	-0.0004	29.77	R	335.0568	1.291	1.706	0.0847	0.0258	0.0344	0.0095
333	8/12/36	-0.0005	-0.0006	0.0002	29.752	G	336.0433	1.384	1.806	0.1232	0.0269	0.0347	0.0096
100	236	100.0016	100.0010	100.0016	29.97	R	457.2843	1.249	1.902	0.1173	0.0242	0.0370	0.0152
333	8/13/36	100.0014	100.0023	0.0004	29.745	G	458.6275	1.322	1.801	0.1420	0.0259	0.0346	0.0152
100	237	100.0008	100.0002	100.0007	30.15	R	457.2807	1.292	1.846	0.1167	0.0250	0.0363	0.0153
333	8/13/36	100.0005	100.0012	0.0003	29.767	G	458.6390	1.359	1.926	0.0785	0.0265	0.0361	0.0153
0	238	-0.0009	-0.0012	-0.0013	30.32	R	335.0703	1.226	1.849	0.0920	0.0247	0.0363	0.0098
333	8/14/36	-0.0018	-0.0014	0.0003	29.826	G	336.0537	1.384	1.883	0.1190	0.0269	0.0356	0.0099
0	239	-0.0011	+0.0004	-0.0004	29.67	R	335.0647	1.305	1.747	0.1107	0.0260	0.0350	0.0095
333	8/14/36	-0.0001	-0.0007	0.0005	29.798	G	336.0550	1.396	1.888	0.1080	0.0271	0.0357	0.0095
150	240	150.0049	150.0005	150.0026	30.72	R	518.2982	1.197	1.879	0.1393	0.0233	0.0367	0.0170
333	8/18/36	150.0012	150.0040	0.0018	29.866	G	519.8533	1.257	1.880	0.0818	0.0249	0.0356	0.0170
150	241	150.0056	150.0016	150.0034	30.92	R	518.3202	1.227	1.886	0.0673	0.0237	0.0368	0.0171
333	8/18/36	150.0021	150.0045	0.0016	29.859	G	519.8577	1.244	1.882	0.0718	0.0247	0.0356	0.0172
100	242	100.0013	99.9995	100.0008	29.92	R	457.2883	1.164	1.862	0.0985	0.0228	0.0365	0.0151
333	8/19/36	100.0005	100.0017	0.0008	29.813	G	458.6457	1.225	1.834	0.1250	0.0242	0.0350	0.0151
100	243	100.0006	99.9985	99.9998	30.14	R	457.3018	1.224	1.727	0.0893	0.0238	0.0347	0.0153
333	8/19/36	99.9992	100.0010	0.0010	29.845	G	458.6583	1.262	1.922	0.0792	0.0249	0.0360	0.0153
150	244	150.0039	149.9994	150.0016	30.29	R	518.3067	1.229	1.931	0.1023	0.0238	0.0374	0.0167
333	8/20/36	150.0006	150.0023	0.0016	29.876	G	519.8403	1.291	1.805	0.1240	0.0255	0.0347	0.0167
150	245	150.0030	149.9983	150.0006	30.15	R	518.3075	1.250	1.737	0.0850	0.0241	0.0348	0.0166
333	8/20/36	149.9994	150.0016	0.0017	29.820	G	519.8445	1.268	1.859	0.1000	0.0251	0.0353	0.0166
0	246	+0.0003	-0.0001	-0.0001	29.34	R	335.0663	1.269	1.904	0.1018	0.0254	0.0370	0.0093
333	8/24/36	-0.0007	+0.0002	0.0003	29.767	G	336.0527	1.440	1.863	0.0888	0.0277	0.0354	0.0094

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
454.6903	0	0.003024	31.0	30.2	30.07	29.877	0.0132	0.1256	0.3619	0.0005	-0.0017	455.190
456.0630	+1	0.003035	31.0	30.0	29.72	29.877	0.0124	0.1081	0.3609	0.0005	-0.0017	456.543
454.7014	-1	0.003020	31.0	30.7	30.26	29.818	0.0131	0.1125	0.3586	0.0005	-0.0020	455.184
456.0544	+2	0.003031	31.0	30.3	30.07	29.818	0.0124	0.1129	0.3616	0.0005	-0.0020	456.540
333.1531	0	0.003439	30.0	30.0	29.69	29.765	0.0143	0.0410	-0.1130	-0.0001	-0.0020	333.093
334.1516	-1	0.003449	30.0	30.0	29.66	29.765	0.0136	0.0349	-0.1128	-0.0001	-0.0020	334.085
333.1693	+1	0.003437	30.0	30.0	29.40	29.743	0.0143	0.0338	-0.1121	-0.0001	0.0006	333.106
334.1597	-1	0.003453	29.0	29.0	29.17	29.743	0.0137	0.0319	-0.1119	-0.0001	0.0006	334.094
515.3691	-2	0.002857	32.0	31.0	30.06	29.734	0.0123	0.1800	0.6987	0.0010	-0.0020	516.259
516.9081	+2	0.002859	31.0	32.0	30.14	29.734	0.0115	0.1771	0.7018	0.0010	-0.0020	517.798
515.3644	+2	0.002852	32.0	31.0	30.22	29.792	0.0122	0.1843	0.6995	0.0010	-0.0007	516.261
516.9014	+3	0.002858	32.0	32.0	30.27	29.792	0.0114	0.1780	0.7015	0.0010	-0.0007	517.793
333.1645	0	0.003436	30.0	30.0	29.65	29.755	0.0143	0.0390	-0.1128	-0.0001	-0.0006	333.104
334.1452	-1	0.003452	29.0	29.3	29.39	29.755	0.0137	0.0428	-0.1132	-0.0001	-0.0006	334.088
333.1657	+1	0.003436	30.0	30.0	29.63	29.749	0.0143	0.0322	-0.1121	-0.0001	0.0005	333.100
334.1475	0	0.003452	29.0	29.5	29.30	29.749	0.0137	0.0387	-0.1128	-0.0001	0.0005	334.088
454.7051	-1	0.003003	31.5	31.0	29.92	29.739	0.0130	0.1238	0.3614	0.0005	-0.0020	455.202
456.0448	-1	0.003010	31.0	31.0	29.87	29.739	0.0122	0.1237	0.3640	0.0005	-0.0020	456.543
454.7013	0	0.002997	32.0	31.0	30.05	29.767	0.0129	0.1220	0.3603	0.0005	-0.0009	455.196
456.0536	+1	0.003008	31.0	31.0	30.03	29.767	0.0122	0.1179	0.3622	0.0005	-0.0009	456.546
333.1720	+1	0.003432	31.0	31.0	30.25	29.826	0.0143	0.0366	-0.1135	-0.0001	0.0016	333.111
334.1528	0	0.003448	30.0	30.0	30.02	29.826	0.0137	0.0400	-0.1138	-0.0001	0.0016	334.094
333.1704	0	0.003434	30.2	30.0	29.55	29.797	0.0143	0.0362	-0.1126	-0.0001	0.0005	333.109
334.1555	-1	0.003453	29.0	29.3	29.27	29.797	0.0137	0.0389	-0.1129	-0.0001	0.0005	334.096
515.3644	-3	0.002863	32.0	32.0	30.67	29.868	0.0123	0.1902	0.7009	0.0010	-0.0032	516.266
516.9134	+1	0.002873	31.7	32.5	30.54	29.868	0.0116	0.1794	0.7017	0.0010	-0.0032	517.804
515.3874	-3	0.002860	32.0	32.0	30.80	29.866	0.0123	0.1777	0.6956	0.0010	-0.0042	516.270
516.9185	+1	0.002872	32.0	32.0	30.59	29.866	0.0116	0.1777	0.7010	0.0010	0.0042	517.806
454.7025	-1	0.003021	31.0	30.5	29.93	29.805	0.0131	0.1196	0.3608	0.0005	-0.0010	455.196
456.0551	+1	0.003027	31.0	31.0	30.05	29.805	0.0124	0.1222	0.3636	0.0005	-0.0010	456.553
454.7163	-1	0.003015	31.0	31.0	30.05	29.847	0.0131	0.1136	0.3588	0.0005	0.0002	455.202
456.0649	0	0.003026	31.0	31.0	30.15	29.847	0.0124	0.1179	0.3623	0.0005	0.0002	456.558
515.3715	-1	0.002874	31.0	31.0	30.19	29.881	0.0124	0.1856	0.7007	0.0010	-0.0020	516.269
516.9007	+1	0.002883	31.0	31.8	29.93	29.881	0.0116	0.1841	0.7050	0.0010	-0.0020	517.800
515.3803	-1	0.002871	31.0	31.0	30.06	29.824	0.0124	0.1753	0.6971	0.0010	-0.0007	516.265
516.9091	+1	0.002883	31.0	32.0	29.81	29.824	0.0116	0.1818	0.7046	0.0010	-0.0007	517.808
333.1711	-1	0.003433	30.0	30.0	29.20	29.759	0.0143	0.0389	-0.1125	-0.0001	0.0001	333.112
334.1559	0	0.003453	29.0	29.0	29.15	29.759	0.0137	0.0361	-0.1124	-0.0001	0.0001	334.093

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TABLE XI (Continued)

t_r / p_o	Run No. / Date	$t_b(308)$ / $t_b(307)$	$t_b(306)$ / $t_b(310)$	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
0	247	0.0000	+0.0005	+0.0003	29.49	R	335.0677	1.310	1.698	0.1070	0.0261	0.0343	0.0094
333	8/24/36	+0.0004	+0.0003	0.0002	29.745	G	336.0535	1.424	1.826	0.1022	0.0275	0.0349	0.0094
100	248	99.9997	99.9982	99.9995	29.69	R	457.2865	1.198	1.880	0.1017	0.0234	0.0367	0.0150
333	8/26/36	99.9991	100.0010	0.0008	29.732	G	458.6462	1.318	1.866	0.1200	0.0258	0.0354	0.0150
100	249	99.9997	99.9985	99.9996	29.50	R	457.2893	1.258	1.701	0.0870	0.0244	0.0343	0.0148
333	8/26/36	99.9991	100.0010	0.0008	29.698	G	458.6448	1.312	1.788	0.0945	0.0257	0.0344	0.0148
0	250	-0.0002	-0.0009	-0.0007	29.30	R	335.0672	1.267	1.924	0.1000	0.0254	0.0373	0.0093
333	8/27/36	-0.0011	-0.0007	0.0003	29.691	G	336.0643	1.398	1.788	0.0818	0.0271	0.0344	0.0093
0	251	+0.0002	-0.0001	-0.0002	29.57	R	335.0692	1.299	1.717	0.0970	0.0259	0.0345	0.0094
333	8/27/36	-0.0007	-0.0001	0.0003	29.692	G	336.0565	1.402	1.750	0.1117	0.0272	0.0340	0.0095
		$t_b(308)$ / $t_b(307)$	$t_b(107)$ / $t_b(310)$										
150	252	150.0076	150.0026	150.0059	29.60	R	518.3085	1.157	1.948	0.0742	0.0226	0.0376	0.0161
333	9/4/36	150.0090	150.0043	0.0024	29.749	G	519.8358	1.216	1.597	0.1215	0.0242	0.0318	0.0161
150	253	150.0071	150.0029	150.0062	29.64	R	518.3038	1.218	1.885	0.0862	0.0236	0.0368	0.0162
333	9/4/36	150.0095	150.0052	0.0021	29.719	G	519.8415	1.303	1.653	0.0943	0.0257	0.0326	0.0162
444.6	254	444.6207	444.6132	444.6179	30.40	R	876.2880	1.091	1.904	0.1042	0.0210	0.0370	0.0297
333	9/8/36	444.6163	444.6214	0.0032	29.884	G	878.9420	1.085	1.351	0.1095	0.0208	0.0279	0.0297
444.6	255	444.6273	444.6198	444.6244	31.07	R	876.3060	1.143	1.881	0.1163	0.0219	0.0368	0.0305
333	9/8/36	444.6226	444.6279	0.0032	29.908	G	878.9463	1.103	1.600	0.1157	0.0211	0.0318	0.0306
150	256	150.0070	150.0042	150.0063	29.45	R	518.3545	1.120	1.913	0.1423	0.0219	0.0372	0.0160
333	9/14/36	150.0084	150.0055	0.0014	29.673	G	519.9230	1.241	1.674	0.1398	0.0246	0.0329	0.0160
150	257	150.0093	150.0071	150.0090	29.37	R	518.3683	1.210	1.942	0.0848	0.0235	0.0375	0.0159
333	9/14/36	150.0109	150.0088	0.0011	29.660	G	519.9437	1.320	1.726	0.1095	0.0260	0.0336	0.0160
444.6	258	444.6264	444.6146	444.6220	29.84	R	876.2653	1.109	1.950	0.0735	0.0213	0.0376	0.0289
333	9/15/36	444.6219	444.6253	0.0038	29.734	G	878.9225	1.145	1.714	0.0748	0.0218	0.0335	0.0290
444.6	259	444.6284	444.6150	444.6234	29.87	R	876.2505	1.181	1.920	0.1218	0.0225	0.0372	0.0290
333	9/15/36	444.6233	444.6268	0.0042	29.739	G	878.9097	1.216	1.707	0.0977	0.0229	0.0334	0.0290
150	260	150.0062	150.0010	150.0058	29.95	R	518.3837	1.168	1.916	0.1247	0.0228	0.0372	0.0164
333	9/17/36	150.0095	150.0065	0.0024	29.772	G	519.9690	1.319	1.893	0.0597	0.0259	0.0357	0.0164
150	261	150.0034	149.9977	150.0026	29.95	R	518.3857	1.220	1.926	0.1153	0.0236	0.0373	0.0164
333	9/17/36	150.0062	150.0031	0.0024	29.776	G	519.9638	1.348	1.804	0.1028	0.0264	0.0346	0.0164
444.6	262	444.6288	444.6128	444.6232	29.59	R	876.2943	1.134	1.931	0.0880	0.0217	0.0374	0.0286
333	9/18/36	444.6222	444.6292	0.0058	29.721	G	878.9511	1.081	1.720	0.1080	0.0207	0.0336	0.0287
444.6	263	444.6270	444.6116	444.6220	29.74	R	876.2920	1.199	1.911	0.1060	0.0228	0.0371	0.0288
333	9/18/36	444.6216	444.6276	0.0054	29.719	G	878.9490	1.184	1.811	0.0992	0.0224	0.0347	0.0289
150	264	149.9980	149.9952	149.9975	29.42	R	518.3923	1.206	1.932	0.0872	0.0234	0.0374	0.0160
333	9/22/36	149.9988	149.9980	0.0012	29.716	G	519.9770	1.246	1.749	0.0895	0.0247	0.0339	0.0160

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
333.1773	0	0.003426	30.0	30.0	29.43	29.739	0.0142	0.0345	-0.1124	-0.0001	-0.0004	333.113
334.1583	0	0.003449	29.0	29.7	29.29	29.739	0.0136	0.0368	-0.1126	-0.0001	-0.0004	334.096
454.7077	-4	0.003023	31.0	30.0	29.62	29.718	0.0131	0.1206	0.3621	0.0005	0.0006	455.205
456.0634	+1	0.003020	30.2	30.8	29.40	29.718	0.0123	0.1225	0.3648	0.0005	0.0006	456.564
454.7164	-4	0.003028	30.8	30.0	29.47	29.688	0.0132	0.1123	0.3607	0.0005	0.0005	455.204
456.0655	+1	0.003024	30.0	30.8	29.22	29.688	0.0123	0.1160	0.3638	0.0005	0.0005	456.559
333.1763	0	0.003437	30.0	29.7	29.16	29.680	0.0143	0.0392	-0.1122	-0.0001	0.0009	333.118
334.1723	0	0.003459	29.0	29.0	28.95	29.680	0.0137	0.0336	-0.1117	-0.0001	0.0009	334.109
333.1816	0	0.003433	30.0	30.0	29.41	29.684	0.0143	0.0338	-0.1120	-0.0001	0.0002	333.118
334.1652	-1	0.003458	29.0	29.0	29.11	29.684	0.0137	0.0360	-0.1121	-0.0001	0.0002	334.103
515.3831	-2	0.002864	30.0	30.0	29.97	29.739	0.0075	0.1811	0.7002	0.0010	-0.0072	516.266
516.9091	+1	0.002834	31.0	30.0	29.19	29.739	0.0084	0.1754	0.7023	0.0010	-0.0072	517.789
515.3831	-1	0.002864	30.0	30.0	29.97	29.713	0.0074	0.1811	0.7003	0.0010	-0.0076	516.265
516.9184	0	0.002835	31.0	30.0	29.21	29.713	0.0084	0.1729	0.7015	0.0010	-0.0076	517.795
871.3326	-3	0.002262	32.0	31.2	30.98	29.910	-0.0023	0.7655	4.0656	0.0069	-0.0219	876.146
873.9804	-2	0.002088	35.0	31.0	30.64	29.910	-0.0021	0.7269	4.0243	0.0068	-0.0219	878.714
871.3486	-2	0.002256	32.0	31.7	31.17	29.943	-0.0024	0.7678	4.0660	0.0069	-0.0298	876.157
873.9782	-1	0.002082	35.0	31.3	30.77	29.943	-0.0022	0.7470	4.0498	0.0069	-0.0299	878.750
515.4356	-1	0.002961	29.0	30.0	29.42	29.654	0.0082	0.1920	0.7105	0.0010	-0.0077	516.340
517.0022	-1	0.002877	30.0	30.0	29.19	29.654	0.0088	0.1817	0.7072	0.0010	-0.0077	517.893
515.4517	-1	0.002961	29.2	30.0	29.33	29.644	0.0082	0.1829	0.7071	0.0010	-0.0110	516.340
517.0247	-1	0.002879	30.0	30.0	29.19	29.644	0.0088	0.1785	0.7061	0.0010	-0.0110	517.908
871.3326	-1	0.002480	30.0	30.0	29.70	29.713	0.0006	0.7591	4.0959	0.0069	-0.0269	876.168
873.9795	-1	0.002305	30.0	30.0	29.35	29.713	0.0009	0.7426	4.0814	0.0069	-0.0269	878.784
871.3188	-1	0.002478	30.0	30.0	29.65	29.726	0.0006	0.7718	4.1130	0.0070	-0.0286	876.183
873.9672	-1	0.002305	30.0	30.0	29.25	29.726	0.0008	0.7489	4.0902	0.0070	-0.0287	878.785
515.4566	-2	0.002962	30.0	30.0	29.79	29.763	0.0082	0.1890	0.7079	0.0010	-0.0071	516.356
517.0376	+2	0.002883	30.0	30.0	29.50	29.763	0.0089	0.1761	0.7040	0.0010	-0.0071	517.920
515.4590	-1	0.002959	30.0	30.0	29.80	29.771	0.0082	0.1877	0.7072	0.0010	-0.0032	516.360
517.0336	+1	0.002882	30.0	30.0	29.47	29.771	0.0088	0.1803	0.7057	0.0010	-0.0032	517.926
871.3638	-4	0.002481	30.0	30.0	29.53	29.692	0.0006	0.7622	4.1018	0.0069	-0.0283	876.207
874.0085	0	0.002310	30.0	30.0	28.99	29.692	0.0009	0.7529	4.0981	0.0070	-0.0284	878.839
871.3634	0	0.002480	30.0	30.0	29.58	29.696	0.0006	0.7666	4.1071	0.0070	-0.0269	876.218
874.0075	+4	0.002310	30.0	30.0	29.10	29.696	0.0009	0.7564	4.1020	0.0070	-0.0269	878.847
515.4704	-1	0.002962	29.0	29.8	29.25	29.699	0.0082	0.1829	0.7070	0.0010	0.0031	516.373
517.0510	+1	0.002884	29.3	29.3	29.08	29.699	0.0089	0.1760	0.7053	0.0010	0.0031	517.945

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TABLE XI (Continued)

t_r / P_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
150	265	149.9982	149.9955	149.9975	29.55	R	518.3933	1.237	1.914	0.0955	0.0239	0.0372	0.0161
333	9/22/36	149.9981	149.9982	0.0010	29.716	G	519.9773	1.295	1.754	0.1030	0.0256	0.0340	0.0161
400	266	400.0032	400.0056	400.0048	30.25	R	822.3055	1.171	1.934	0.0990	0.0222	0.0374	0.0277
333	9/23/36	400.0032	400.0071	0.0016	29.782	G	824.8013	1.154	1.840	0.1003	0.0224	0.0351	0.0278
356.58	267	356.5776	356.5782	356.5774	30.29	R	769.6923	1.181	1.929	0.1098	0.0223	0.0373	0.0262
333	9/24/36	356.5762	356.5774	0.0006	29.782	G	772.0612	1.258	1.837	0.0710	0.0246	0.0350	0.0262
300	268	299.9993	299.9968	299.9976	29.87	R	700.9952	1.118	1.928	0.1150	0.0213	0.0373	0.0237
333	9/24/36	299.9972	299.9973	0.0008	29.757	G	703.1445	1.050	1.873	0.0855	0.0215	0.0355	0.0237
250	269	250.0064	250.0052	250.0054	29.69	R	640.2400	1.156	1.930	0.0823	0.0220	0.0374	0.0198
333	9/25/36	250.0050	250.0048	0.0006	29.677	G	642.1908	1.215	1.794	0.0918	0.0244	0.0345	0.0199
200	270	200.0069	200.0054	200.0063	29.79	R	579.3825	1.177	1.884	0.1143	0.0226	0.0368	0.0171
333	9/28/36	200.0071	200.0057	0.0007	29.756	G	581.1592	1.203	1.688	0.1030	0.0241	0.0331	0.0172
150	271	150.0018	149.9966	149.9992	29.45	R	518.4138	1.240	1.948	0.0928	0.0239	0.0376	0.0160
333	9/29/36	149.9987	149.9995	0.0015	29.656	G	519.9933	1.231	1.870	0.1117	0.0245	0.0354	0.0160
150	272	150.0012	149.9957	149.9986	29.37	R	518.4203	1.244	1.914	0.0992	0.0240	0.0372	0.0159
333	9/29/36	149.9983	149.9993	0.0016	29.674	G	519.9925	1.243	1.807	0.1428	0.0247	0.0347	0.0160
444.6	273	444.6354	444.6416	444.6398	29.45	R	876.3755	1.130	1.930	0.0877	0.0217	0.0374	0.0284
333	10/1/36	444.6390	444.6434	0.0026	29.680	G	879.0603	1.102	1.335	0.0847	0.0211	0.0276	0.0285
444.6	274	444.6292	444.6346	444.6330	29.52	R	876.3657	1.160	1.897	0.1008	0.0222	0.0370	0.0285
333	10/1/36	444.6322	444.6360	0.0023	29.712	G	879.0303	1.153	1.798	0.1043	0.0219	0.0346	0.0286
150	275	150.0020	149.9996	150.0006	29.37	R	518.4288	1.260	1.928	0.1097	0.0243	0.0373	0.0159
333	10/5/36	150.0007	150.0000	0.0008	29.683	G	520.0342	1.278	1.927	0.1032	0.0253	0.0361	0.0160
150	276	149.9996	149.9982	149.9988	29.45	R	518.4323	1.257	1.908	0.1027	0.0242	0.0371	0.0160
333	10/5/36	149.9990	149.9985	0.0005	29.694	G	520.0383	1.283	1.813	0.1042	0.0254	0.0348	0.0160
150	277	149.9983	149.9955	149.9975	29.37	R	518.4820	1.243	1.911	0.1045	0.0240	0.0371	0.0159
333	10/13/36	149.9980	149.9982	0.0010	29.638	G	520.1417	1.227	1.893	0.0665	0.0244	0.0357	0.0160
150	278	149.9988	149.9963	149.9980	29.37	R	518.4748	1.249	1.903	0.1197	0.0241	0.0370	0.0159
333	10/13/36	149.9986	149.9981	0.0008	29.638	G	520.1330	1.243	1.785	0.1250	0.0247	0.0344	0.0160
444.6	279	444.5989	444.6011	444.6003	29.45	R	876.3933	1.210	1.910	0.1272	0.0230	0.0371	0.0284
333	10/14/36	444.6008		0.0009	29.672	G	879.1845	1.177	1.848	0.1020	0.0223	0.0352	0.0285
444.6	280	444.5932	444.5928	444.5928	29.47	R	876.4018	1.187	1.911	0.1053	0.0226	0.0371	0.0284
333	10/14/36	444.5925		0.0002	29.685	G	879.1728	1.199	1.842	0.1030	0.0227	0.0351	0.0285
150	281	149.9992	149.9964	149.9984	29.37	R	518.4793	1.269	1.913	0.1020	0.0244	0.0372	0.0159
333	10/16/36	149.9996		0.0013	29.698	G	520.1250	1.336	1.855	0.1013	0.0262	0.0353	0.0160
150	282	149.9989	149.9972	149.9989	29.42	R	518.4852	1.254	1.923	0.0872	0.0242	0.0373	0.0160
333	10/16/36	150.0007		0.0012	29.712	G	520.1203	1.285	1.795	0.1433	0.0254	0.0345	0.0160
444.6	283	444.6029	444.5997	444.6039	29.59	R	876.4172	1.331	1.915	0.1073	0.0249	0.0372	0.0286
333	10/19/36	444.6061	444.6069	0.0026	29.688	G	879.1568	1.200	1.848	0.1070	0.0227	0.0352	0.0287

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
515.4722	-1	0.002962	29.5	30.0	29.41	29.705	0.0082	0.1838	0.7069	0.0010	0.0031	516.375
517.0521	+1	0.002885	30.0	30.0	29.21	29.705	0.0088	0.1785	0.7059	0.0010	0.0031	517.949
817.6701	-2	0.002526	30.0	30.0	30.03	29.776	0.0018	0.6613	3.4364	0.0058	-0.0059	821.770
820.1544	+2	0.002355	31.0	30.0	29.67	29.776	0.0020	0.6545	3.4339	0.0058	-0.0059	824.245
765.3530	-3	0.002579	30.0	30.7	30.09	29.782	0.0029	0.5665	2.8422	0.0048	0.0032	768.773
767.7131	-1	0.002422	31.0	30.2	29.70	29.782	0.0033	0.5498	2.8299	0.0048	0.0032	771.104
697.0439	-3	0.002666	30.0	30.0	29.79	29.745	0.0045	0.4483	2.1447	0.0035	0.0029	699.648
699.1830	+1	0.002524	30.0	30.0	29.60	29.745	0.0049	0.4373	2.1382	0.0035	0.0029	701.770
636.6377	-1	0.002748	30.0	30.0	29.59	29.654	0.0057	0.3443	1.5936	0.0026	-0.0066	638.577
638.5829	+2	0.002625	30.0	30.0	29.45	29.654	0.0063	0.3393	1.5922	0.0026	-0.0066	640.517
576.1133	-2	0.002843	29.8	30.0	29.65	29.747	0.0070	0.2620	1.1174	0.0017	-0.0077	577.494
577.8853	0	0.002743	30.0	30.0	29.50	29.747	0.0076	0.2506	1.1127	0.0017	-0.0077	579.250
515.4977	-1	0.002957	29.7	30.0	29.50	29.631	0.0082	0.1845	0.7072	0.0010	0.0010	516.400
517.0711	+1	0.002879	30.0	30.0	29.41	29.631	0.0088	0.1843	0.7081	0.0010	0.0010	517.974
515.5029	-1	0.002955	29.0	30.0	29.34	29.654	0.0081	0.1844	0.7074	0.0010	0.0017	516.406
517.0695	0	0.002879	30.0	30.0	29.15	29.654	0.0088	0.1874	0.7096	0.0010	0.0017	517.978
871.4508	-4	0.002473	30.0	30.0	29.42	29.642	0.0004	0.7621	4.1025	0.0070	-0.0486	876.274
874.1297	-2	0.002312	30.0	30.0	29.05	29.642	0.0009	0.7184	4.0524	0.0069	-0.0488	878.860
871.4370	-3	0.002469	30.0	30.0	29.41	29.684	0.0004	0.7640	4.1040	0.0070	-0.0403	876.272
874.0888	0	0.002309	30.0	30.0	29.06	29.684	0.0009	0.7569	4.1037	0.0070	-0.0404	878.917
515.5107	-1	0.002958	29.0	30.0	29.26	29.659	0.0082	0.1868	0.7086	0.0010	-0.0007	516.415
517.1093	+1	0.002886	30.0	29.0	29.14	29.659	0.0089	0.1848	0.7092	0.0010	-0.0007	518.012
515.5133	-1	0.002958	29.0	30.0	29.35	29.680	0.0082	0.1848	0.7075	0.0010	0.0015	516.416
517.1138	0	0.002885	29.8	29.7	29.08	29.680	0.0088	0.1809	0.7074	0.0010	0.0015	518.013
515.5677	-1	0.002955	29.0	30.0	29.31	29.612	0.0081	0.1853	0.7081	0.0010	0.0031	516.473
517.2199	0	0.002887	30.0	29.7	29.04	29.612	0.0089	0.1772	0.7066	0.0010	0.0031	518.117
515.5607	-1	0.002953	29.0	30.0	29.29	29.619	0.0081	0.1877	0.7090	0.0010	0.0024	516.469
517.2129	+1	0.002885	30.0	30.0	29.03	29.619	0.0088	0.1836	0.7089	0.0010	0.0024	518.118
871.4714	-2	0.002467	30.0	30.0	29.35	29.633	0.0003	0.7728	4.1166	0.0070	-0.0004	876.368
874.2481	-1	0.002301	30.0	30.0	29.14	29.633	0.0008	0.7594	4.1071	0.0070	-0.0004	879.122
871.4774	-2	0.002467	30.0	30.0	29.31	29.659	0.0003	0.7663	4.1074	0.0070	0.0088	876.367
874.2350	+1	0.002301	30.0	30.0	29.13	29.659	0.0008	0.7594	4.1064	0.0070	0.0088	879.117
515.5597	-2	0.002957	29.0	29.8	29.28	29.678	0.0082	0.1849	0.7078	0.0010	0.0020	516.464
517.1999	-2	0.002891	29.7	29.3	29.11	29.678	0.0089	0.1819	0.7082	0.0010	0.0020	518.102
515.5641	-3	0.002956	29.0	30.0	29.33	29.699	0.0082	0.1826	0.7066	0.0010	0.0013	516.464
517.1939	-1	0.002889	29.8	29.3	29.11	29.699	0.0089	0.1871	0.7101	0.0011	0.0013	518.102
871.4946	-1	0.002466	29.8	30.0	29.40	29.663	0.0004	0.7672	4.1082	0.0070	-0.0048	876.373
874.2187	+2	0.002297	30.5	30.0	29.18	29.663	0.0007	0.7608	4.1077	0.0070	-0.0048	879.090

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TABLE XI (Continued)

t_r / P_o	Run No. / Date	t_b(308) / t_b(307)	t_b(107) / t_b(310)	t_b(ave.) / Ave. dev.	t_a / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
444.6	284	444.5986	444.5986	444.6024	29.60	R	876.3978	1.331	1.893	0.1255	0.0249	0.0369	0.0286
333	10/19/36	444.6038	444.6055	0.0023	29.698	G	879.1745	1.190	1.873	0.0832	0.0225	0.0355	0.0287
150	285		149.9928	149.9957	29.65	R	518.4662	1.261	1.916	0.1042	0.0243	0.0372	0.0162
333	10/21/36	149.9973	149.9970	0.0019	29.722	G	520.1112	1.333	1.806	0.0945	0.0262	0.0347	0.0162
150	286		149.9983	150.0009	29.57	R	518.4697	1.273	1.877	0.1087	0.0245	0.0367	0.0161
333	10/21/36	150.0025	150.0020	0.0018	29.717	G	520.1053	1.313	1.858	0.0957	0.0258	0.0353	0.0161
150	287	150.0010	149.9970	149.9981	28.75	R	518.4645	1.309	1.941	0.1052	0.0250	0.0375	0.0155
333	10/28/36	149.9987	149.9958	0.0017	29.682	G	520.1042	1.348	1.876	0.0882	0.0264	0.0355	0.0155
150	288	150.0009	149.9980	149.9986	28.84	R	518.4643	1.277	1.894	0.1132	0.0245	0.0369	0.0155
333	10/28/36	149.9996	149.9960	0.0016	29.685	G	520.1078	1.362	1.880	0.0713	0.0266	0.0356	0.0155
400	289	399.9986	399.9960	399.9972	29.34	R	822.4197	1.186	1.882	0.0970	0.0224	0.0368	0.0266
333	10/29/36	399.9966	399.9978	0.0010	29.745	G	824.9875	1.206	1.896	0.0945	0.0233	0.0358	0.0267
356.58	290	356.5721	356.5707	356.5695	29.20	R	769.7767	1.154	1.909	0.1050	0.0219	0.0371	0.0249
333	10/29/36	356.5690	356.5661	0.0019	29.744	G	772.1897	1.219	1.916	0.0765	0.0239	0.0360	0.0250
200	291	200.0011	199.9998	199.9985	29.24	R	579.4363	1.136	1.948	0.0925	0.0219	0.0376	0.0166
333	10/30/36	199.9980	199.9951	0.0020	29.729	G	581.2497	1.260	1.771	0.0997	0.0251	0.0342	0.0167
150	292	150.0011	149.9976	149.9986	29.25	R	518.4713	1.263	1.874	0.1137	0.0243	0.0367	0.0158
333	10/31/36	149.9993	149.9962	0.0016	29.732	G	520.1002	1.363	1.897	0.1078	0.0266	0.0358	0.0159
150	293	150.0018	149.9973	149.9987	29.24	R	518.4748	1.305	1.862	0.1048	0.0250	0.0365	0.0158
333	10/31/36	149.9992	149.9964	0.0018	29.733	G	520.1075	1.370	1.932	0.0660	0.0268	0.0362	0.0159
356.58	294	356.5805	356.5781	356.5780	29.75	R	769.7888	1.146	1.933	0.1118	0.0217	0.0374	0.0255
333	11/2/36	356.5773	356.5762	0.0013	29.810	G	772.2048	1.172	1.874	0.0800	0.0231	0.0355	0.0256
300	295	300.0002	299.9972	299.9972	30.02	R	701.1103	1.248	1.932	0.1045	0.0218	0.0374	0.0239
333	11/3/36	299.9972	299.9942	0.0015	29.841	G	703.2937	1.246	1.876	0.0862	0.0250	0.0355	0.0239
250	296	250.0008	249.9995	249.9980	29.65	R	640.3070	1.127	1.918	0.1220	0.0216	0.0372	0.0198
333	11/3/36	249.9976	249.9940	0.0022	29.838	G	642.3140	1.191	1.878	0.0845	0.0240	0.0355	0.0199
150	297	150.0019	149.9989	149.9992	29.44	R	518.4533	1.286	1.927	0.1138	0.0247	0.0373	0.0160
333	11/5/36	149.9995	149.9965	0.0015	29.633	G	520.0852	1.363	1.858	0.0935	0.0266	0.0353	0.0160
150	298	150.0029	149.9981	149.9992	29.47	R	518.4577	1.278	1.926	0.1083	0.0246	0.0373	0.0160
333	11/5/36	149.9992	149.9968	0.0018	29.617	G	520.0798	1.369	1.823	0.1000	0.0267	0.0349	0.0160
250	299	249.9991	249.9960	249.9956	29.44	R	640.2702	1.193	1.886	0.1310	0.0227	0.0368	0.0195
333	11/6/36	249.9946	249.9929	0.0019	29.597	G	642.2682	1.222	1.947	0.1135	0.0245	0.0363	0.0197
300	300	300.0017	299.9991	299.9978	29.85	R	701.0977	1.222	1.907	0.0990	0.0230	0.0371	0.0237
333	11/6/36	299.9972	299.9933	0.0026	29.648	G	703.2743	1.224	1.902	0.0768	0.0246	0.0358	0.0237
356.58	301	356.5822	356.5855	356.5804	29.89	R	769.7755	1.197	1.871	0.1157	0.0226	0.0366	0.0257
333	11/7/36	356.5776	356.5765	0.0034	29.662	G	772.1530	1.202	1.871	0.1085	0.0237	0.0355	0.0258
150	302	149.9979	149.9904	149.9937	29.85	R	518.4588	1.248	1.915	0.0980	0.0241	0.0372	0.0163
333	11/9/36	149.9951	149.9914	0.0028	29.675	G	520.0735	1.358	1.740	0.1085	0.0266	0.0338	0.0164

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_I}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
871.4740	-1	0.002464	29.7	30.0	29.40	29.680	0.0003	0.7713	4.1132	0.0070	-0.0029	876.363
874.2342	+2	0.002298	30.0	30.0	29.12	29.680	0.0007	0.7555	4.1004	0.0070	-0.0029	879.095
515.5446	-2	0.002952	30.0	30.0	29.59	29.707	0.0081	0.1854	0.7068	0.0010	0.0053	516.451
517.1847	+1	0.002891	29.8	30.0	29.33	29.707	0.0089	0.1790	0.7063	0.0010	0.0053	518.085
515.5492	-1	0.002952	30.0	30.0	29.55	29.707	0.0081	0.1848	0.7066	0.0010	-0.0011	516.449
517.1782	+2	0.002891	30.0	30.0	29.30	29.707	0.0089	0.1812	0.7072	0.0010	-0.0011	518.075
515.5464	-4	0.002955	29.0	29.0	28.75	29.650	0.0081	0.1863	0.7096	0.0010	0.0023	516.454
517.1802	0	0.002883	29.0	29.0	28.70	29.650	0.0088	0.1804	0.7083	0.0010	0.0023	518.081
515.5460	-3	0.002955	29.0	29.0	28.76	29.659	0.0081	0.1861	0.7095	0.0010	0.0017	516.452
517.1836	0	0.002883	29.0	29.0	28.59	29.659	0.0088	0.1776	0.7073	0.0010	0.0017	518.080
817.7889	-2	0.002521	29.3	30.0	29.20	29.726	0.0016	0.6578	3.4368	0.0058	0.0034	821.894
820.3442	+1	0.002354	30.0	30.0	28.92	29.726	0.0019	0.6561	3.4405	0.0058	0.0034	824.452
765.4407	-2	0.002576	29.2	30.0	29.09	29.722	0.0028	0.5643	2.8451	0.0048	0.0128	768.870
767.8433	-1	0.002418	30.0	30.0	29.00	29.722	0.0032	0.5555	2.8396	0.0048	0.0129	771.259
576.1677	-12	0.002842	29.2	29.8	29.13	29.709	0.0069	0.2599	1.1180	0.0017	0.0018	577.556
577.9775	-10	0.002739	30.0	29.5	29.05	29.709	0.0075	0.2532	1.1157	0.0017	0.0018	579.357
515.5489	-3	0.002951	29.3	30.0	29.23	29.718	0.0081	0.1855	0.7075	0.0010	0.0017	516.453
517.1719	0	0.002873	30.0	30.0	29.27	29.718	0.0088	0.1846	0.7078	0.0010	0.0017	518.076
515.5532	-1	0.002948	29.3	30.0	29.15	29.722	0.0081	0.1836	0.7067	0.0010	0.0016	516.454
517.1788	0	0.002873	30.0	30.0	29.21	29.722	0.0088	0.1785	0.7055	0.0010	0.0016	518.074
765.4437	0	0.002576	29.2	30.0	29.55	29.797	0.0029	0.5674	2.8457	0.0048	0.0024	768.867
767.8494	+3	0.002419	30.0	30.0	29.26	29.797	0.0032	0.5545	2.8365	0.0048	0.0024	771.251
697.1483	-2	0.002651	30.0	30.2	29.85	29.839	0.0043	0.4461	2.1405	0.0035	0.0034	699.746
699.3244	+2	0.002513	30.0	30.0	29.62	29.839	0.0048	0.4378	2.1370	0.0035	0.0034	701.911
636.6856	-2	0.002737	29.8	30.0	29.55	29.828	0.0056	0.3525	1.5975	0.0026	0.0024	638.646
638.6854	+1	0.002612	30.0	30.0	29.36	29.828	0.0061	0.3415	1.5919	0.0026	0.0024	640.630
515.5402	-2	0.002952	29.2	30.0	29.32	29.621	0.0081	0.1875	0.7087	0.0010	0.0010	516.446
517.1668	0	0.002875	29.8	29.8	29.12	29.621	0.0088	0.1807	0.7073	0.0010	0.0010	518.066
515.5460	-2	0.002952	29.5	30.0	29.36	29.604	0.0081	0.1865	0.7083	0.0010	0.0010	516.451
517.1634	0	0.002875	30.0	30.0	29.23	29.604	0.0088	0.1805	0.7070	0.0010	0.0010	518.062
636.6780	-3	0.002742	29.7	30.0	29.32	29.579	0.0056	0.3530	1.6010	0.0026	0.0054	638.646
638.6673	+2	0.002623	30.0	30.0	28.99	29.579	0.0062	0.3507	1.6024	0.0026	0.0054	640.635
697.1615	-2	0.002654	30.0	30.0	29.75	29.635	0.0044	0.4436	2.1411	0.0035	0.0027	699.757
699.3287	+3	0.002515	30.2	30.0	29.50	29.635	0.0048	0.4368	2.1388	0.0035	0.0027	701.915
765.4529	0	0.002570	30.0	30.0	29.80	29.648	0.0028	0.5652	2.8433	0.0048	-0.0005	768.868
767.8193	+2	0.002417	31.0	30.0	29.67	29.648	0.0032	0.5616	2.8443	0.0048	-0.0005	771.233
515.5416	-3	0.002952	30.0	30.0	29.84	29.663	0.0081	0.1842	0.7061	0.0010	0.0077	516.449
517.1531	0	0.002873	30.0	30.0	29.65	29.663	0.0088	0.1789	0.7052	0.0010	0.0077	518.055

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TABLE XI (Continued)

t_r p_o	Run No. Date	$t_b(308)$ $t_b(307)$	$t_b(107)$ $t_b(310)$	t_b(ave.) Ave. dev.	t_s t_{H_4}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
150	303	150.0010	149.9924	149.9960	29.87	R	518.4543	1.300	1.880	0.1263	0.0249	0.0367	0.0164
333	11/9/36	149.9964	149.9940	0.0028	29.662	G	520.0800	1.392	1.858	0.0928	0.0271	0.0353	0.0164
200	304	200.0026	199.9986	199.9993	29.69	R	579.4257	1.185	1.841	0.1132	0.0227	0.0362	0.0170
333	11/10/36	199.9993	199.9968	0.0016	29.679	G	581.2135	1.251	1.910	0.1207	0.0249	0.0359	0.0171
400	305	399.9970	399.9949	399.9938	29.39	R	822.3800	1.196	1.911	0.1048	0.0226	0.0371	0.0267
333	11/11/36	399.9918	399.9915	0.0022	29.629	G	824.9048	1.216	1.912	0.1152	0.0234	0.0359	0.0267
356.58	306	356.5813		356.5798	29.20	R	769.7617	1.209	1.897	0.1095	0.0227	0.0370	0.0249
333	11/12/36	356.5783	356.5798	0.0010	29.640	G	772.1322	1.204	1.860	0.0907	0.0237	0.0353	0.0250
150	307	150.0020		149.9978	29.22	R	518.4557	1.265	1.908	0.1095	0.0243	0.0371	0.0158
333	11/14/36	149.9978	149.9936	0.0028	29.629	G	520.0640	1.366	1.844	0.1043	0.0267	0.0351	0.0158
		$t_b(308)$ $t_b(307)$	$t_b(306)$ $t_b(310)$										
150	308	150.0021		149.9984	29.19	R	518.4543	1.298	1.918	0.1125	0.0249	0.0372	0.0158
333	11/14/36	149.9987	149.9944	0.0027	29.626	G	520.0680	1.398	1.856	0.0918	0.0272	0.0353	0.0158
150	309	150.0020	149.9967	149.9976	28.84	R	934.3990	1.156	1.952	0.0883	0.0223	0.0376	0.0300
600	11/25/36	149.9956	149.9963	0.0022	29.542	G	935.4130	1.092	1.546	0.0865	0.0210	0.0310	0.0301
150	310	150.0012	149.9960	149.9965	28.84	R	934.4052	1.180	1.917	0.0945	0.0227	0.0372	0.0300
600	11/25/36	149.9945	149.9942	0.0024	29.574	G	934.3998	1.148	1.445	0.1017	0.0219	0.0294	0.0301
150	311	149.9990	149.9988	149.9979	29.20	R	934.4430	1.119	1.958	0.1053	0.0217	0.0377	0.0305
600	12/15/36	149.9962	149.9976	0.0010	29.643	G	935.3183	1.064	1.388	0.0882	0.0205	0.0285	0.0306
150	312	149.9990	149.9996	149.9982	29.20	R	934.4500	1.169	1.950	0.0912	0.0225	0.0376	0.0305
600	12/15/36	149.9962	149.9979	0.0011	29.644	G	935.3167	1.113	1.562	0.0777	0.0214	0.0312	0.0306
444.6	313			444.5974	29.37	R	1579.8742	1.096	1.923	0.1228	0.0216	0.0373	0.0568
600	12/16/36	444.6008	444.5940	0.0034	29.668	G	1581.3590	1.051	1.419	0.0945	0.0211	0.0290	0.0569
444.6	314			444.5964	29.37	R	1579.9135	1.159	1.907	0.0960	0.0226	0.0371	0.0568
600	12/16/36	444.5985	444.5942	0.0022	29.669	G	1581.3223	1.086	1.604	0.0818	0.0217	0.319	0.0569
150	315		150.0014	150.0016	29.15	R	934.4578	1.084	1.893	0.1257	0.0211	0.0369	0.0305
600	12/18/36	150.0000	150.0033	0.0012	29.598	G	935.3242	1.043	1.368	0.1085	0.0202	0.0282	0.0305
150	316		150.0026	150.0025	29.15	R	934.4688	1.163	1.795	0.1233	0.0224	0.0356	0.0305
600	12/18/36	149.9996	150.0054	0.0020	29.606	G	935.3353	1.144	1.378	0.1037	0.0219	0.0283	0.0305
444.6	317		444.5809	444.5883	30.07	R	1579.9007	1.140	1.923	0.0960	0.0223	0.0373	0.0585
600	12/19/36	444.5948	444.5891	0.0049	29.676	G	1581.3158	1.094	1.476	0.0960	0.0218	0.0299	0.0585
444.6	318		444.5848	444.5905	29.80	R	1579.9122	1.213	1.881	0.0945	0.0235	0.0368	0.0579
600	12/19/36	444.5953	444.5913	0.0038	29.681	G	1581.3180	1.166	1.693	0.0845	0.0231	0.0332	0.0579
150	319		149.9951	149.9993	29.67	R	934.4898	1.050	1.928	0.1147	0.0205	0.0373	0.0312
600	12/21/36	150.0000	150.0029	0.0028	29.673	G	935.3525	0.984	1.385	0.1135	0.0191	0.0284	0.0313
150	320		149.9980	150.0015	29.29	R	934.4867	1.186	1.934	0.0780	0.0228	0.0374	0.0307
600	12/21/36	150.0034	150.0032	0.0024	29.657	G	935.3388	1.157	1.540	0.0922	0.0221	0.0309	0.0307

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_n	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
515.5397	-3	0.002951	30.0	30.0	29.82	29.650	0.0081	0.1880	0.7077	0.0010	0.0049	516.449
517.1598	0	0.002872	30.0	30.0	29.56	29.650	0.0088	0.1806	0.7061	0.0010	0.0049	518.061
576.1649	-4	0.002833	29.8	30.0	29.61	29.669	0.0069	0.2600	1.1164	0.0017	0.0009	577.551
577.9452	0	0.002729	30.0	30.0	29.49	29.669	0.0075	0.2634	1.1199	0.0017	0.0009	579.339
817.7666	+97	0.002510	30.0	30.0	29.35	29.608	0.0015	0.6671	3.4409	0.0058	0.0076	821.890
820.2792	+99	0.002352	31.0	30.0	29.32	29.608	0.0019	0.6688	3.4480	0.0059	0.0076	824.411
765.4411	-5	0.002566	30.0	30.0	29.12	29.629	0.0027	0.5647	2.8456	0.0048	0.0002	768.859
767.8011	-5	0.002414	30.0	30.0	29.34	29.629	0.0032	0.5560	2.8400	0.0048	0.0002	771.205
515.5426	-5	0.002956	29.3	30.0	29.19	29.614	0.0081	0.1859	0.7086	0.0010	0.0027	516.449
517.1462	-2	0.002879	30.0	29.7	29.26	29.614	0.0088	0.1820	0.7077	0.0010	0.0027	518.048
515.5420	0	0.002952	29.0	30.0	29.20	29.612	0.0081	0.1870	0.7088	0.0010	0.0020	516.449
517.1508	+1	0.002876	30.0	30.0	29.15	29.612	0.0088	0.1803	0.7071	0.0010	0.0020	518.050
929.1726	-2	0.002961	29.0	29.2	29.28	29.495	0.0148	0.3300	1.2773	0.0034	0.0053	930.803
930.1863	-2	0.002902	30.0	29.0	28.95	29.495	0.0162	0.2992	1.2665	0.0034	0.0053	931.777
929.1742	0	0.002952	29.0	29.0	29.05	29.529	0.0146	0.3299	1.2770	0.0034	0.0077	930.807
930.1703	-1	0.002889	29.8	29.0	28.95	29.529	0.0160	0.2962	1.2640	0.0034	0.0077	931.758
929.1992	-3	0.002946	30.0	30.0	29.35	29.625	0.0145	0.3357	1.2762	0.0034	0.0046	930.834
930.0776	-2	0.002895	30.0	30.0	29.39	29.625	0.0161	0.2874	1.2580	0.0033	0.0046	931.647
929.2069	-3	0.002943	30.0	30.0	29.46	29.629	0.0145	0.3307	1.2736	0.0034	0.0040	930.833
930.0741	-1	0.002894	30.0	30.0	29.50	29.629	0.0161	0.2977	1.2616	0.0033	0.0040	931.657
1571.0178	-4	0.002452	31.0	30.0	29.40	29.652	0.0002	1.3885	7.4145	0.0227	0.0057	1581.145
1572.5021	-2	0.002317	31.0	30.0	29.55	29.652	0.0018	1.3054	7.3079	0.0224	0.0057	1581.145
1571.0578	+2	0.002451	31.0	30.0	29.44	29.663	0.0002	1.3729	7.3915	0.0226	0.0079	1579.853
1572.4630	0	0.002315	31.0	30.0	29.61	29.663	0.0018	1.3229	7.3301	0.0224	0.0079	1581.148
929.2217	-2	0.002946	30.0	30.0	29.47	29.575	0.0145	0.3382	1.2774	0.0034	-0.0035	930.852
930.0910	-2	0.002895	30.0	30.0	29.40	29.575	0.0161	0.2922	1.2604	0.0033	-0.0035	931.660
929.2339	-3	0.002947	30.0	30.0	29.45	29.590	0.0145	0.3308	1.2745	0.0034	-0.0055	930.852
930.1023	-1	0.002896	30.0	30.0	29.41	29.590	0.0161	0.2916	1.2601	0.0033	-0.0055	931.668
1571.0443	-4	0.002451	31.0	31.0	30.20	29.663	0.0003	1.3741	7.3850	0.0225	0.0258	1579.852
1572.4583	-1	0.002317	31.8	31.0	30.14	29.663	0.0018	1.3138	7.3119	0.0223	0.0258	1581.134
1571.0554	-4	0.002452	31.0	30.2	29.88	29.680	0.0003	1.3687	7.3816	0.0225	0.0209	1579.849
1572.4564	+2	0.002317	31.0	30.0	29.79	29.680	0.0019	1.3355	7.3454	0.0225	0.0209	1581.183
929.2406	-3	0.002932	30.0	30.0	29.85	29.663	0.0144	0.3369	1.2736	0.0034	0.0015	930.870
930.1060	-2	0.002873	30.5	30.0	29.89	29.663	0.0158	0.2951	1.2576	0.0033	0.0015	931.679
929.2419	-4	0.002938	30.0	30.0	29.47	29.650	0.0144	0.3255	1.2710	0.0034	-0.0033	930.853
930.0950	-1	0.002876	30.0	30.0	29.35	29.650	0.0158	0.3006	1.2618	0.0033	-0.0033	931.673

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TABLE XI (Continued)

t_r / p_o	Run No. / Date	$t_b(310)$ / $t_b(312)$	$t_b(313)$ / $t_b(314)$	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
150	321	150.0044	150.0036	150.0040	28.67	R	934.5270	1.124	1.869	0.1012	0.0217	0.0366	0.0298
600	2/18/37	150.0058	150.0021	0.0011	29.566	G	935.3937	1.152	1.464	0.0900	0.0220	0.0297	0.0299
150	322	150.0044	150.0041	150.0040	28.70	R	934.5250	1.129	1.880	0.1050	0.0218	0.0367	0.0298
600	2/18/37	150.0056	150.0019	0.0010	29.561	G	935.3832	1.114	1.355	0.1087	0.0214	0.0279	0.0299
444.6	323	444.6049	444.6054	444.6055	28.94	R	1580.0220	1.199	1.950	0.0920	0.0233	0.0376	0.0558
600	2/19/37	444.6068	444.6048	0.0007	29.607	G	1581.4752	1.191	1.549	0.0765	0.0236	0.0310	0.0559
444.6	324	444.6050	444.6030	444.6039	29.09	R	1580.0462	1.194	1.917	0.1220	0.0232	0.0372	0.0562
600	2/20/37	444.6044	444.6032	0.0008	29.707	G	1581.5398	1.094	1.497	0.1078	0.0218	0.0303	0.0562
150	325	149.9997	149.9962	149.9972	29.27	R	934.5805	1.069	1.935	0.1120	0.0208	0.0374	0.0307
600	2/25/37	150.0008	149.9921	0.0030	29.619	G	935.4783	0.987	1.374	0.1250	0.0192	0.0283	0.0307
150	326	149.9997	149.9965	149.9973	29.24	R	934.5745	1.136	1.869	0.0878	0.0220	0.0366	0.0306
600	2/25/37	150.0006	149.9924	0.0028	29.639	G	935.4527	1.182	1.691	0.1245	0.0225	0.0332	0.0307
150	327	149.9996	150.0003	149.9998	29.27	R	934.6568	1.133	1.920	0.0977	0.0219	0.0372	0.0307
600	3/3/37	150.0025	149.9966	0.0016	29.686	G	935.6078	1.242	1.374	0.0890	0.0235	0.0283	0.0307
150	328	150.0002	150.0007	150.0004	29.40	R	934.6437	1.186	1.916	0.1222	0.0228	0.0372	0.0308
600	3/3/37	150.0031	149.9975	0.0015	29.685	G	935.5920	1.256	1.500	0.1093	0.0237	0.0303	0.0309
444.6	329	444.6055	444.6026	444.6020	29.42	R	1580.2203	1.144	1.920	0.1092	0.0224	0.0372	0.0570
600	3/4/37	444.6025	444.6025	0.0008	29.703	G	1581.7973	1.129	1.709	0.0973	0.0225	0.0334	0.0570
444.6	330	444.6011	444.6014	444.6014	29.32	R	1580.2007	1.183	1.850	0.1208	0.0231	0.0363	0.0567
600	3/4/37	444.6010	444.6020	0.0003	29.661	G	1581.7613	1.140	1.449	0.1115	0.0227	0.0295	0.0568
150	331	150.0017	150.0017	150.0016	28.65	R	934.6090	1.116	1.932	0.1077	0.0216	0.0374	0.0298
600	3/6/37	150.0041	149.9988	0.0014	29.463	G	935.5323	1.096	1.692	0.1097	0.0211	0.0332	0.0298
150	332	150.0014	150.0009	150.0011	28.69	R	934.6073	1.208	1.835	0.1073	0.0232	0.0362	0.0298
600	3/6/37	150.0038	149.9982	0.0015	29.489	G	935.5378	1.255	1.691	0.1043	0.0237	0.0332	0.0299
200	333	200.0031	200.0009	200.0015	28.97	R	1044.5988	1.206	1.900	0.1035	0.0233	0.0370	0.0349
600	3/8/37	199.9993	200.0028	0.0014	29.618	G	1045.6153	1.235	1.619	0.1198	0.0245	0.0321	0.0349
400	334	399.9982	400.0008	399.9999	29.20	R	1482.8522	1.100	1.918	0.0917	0.0218	0.0372	0.0538
600	3/9/37	400.0006	400.0001	0.0009	29.677	G	1484.2785	0.805	1.750	0.1110	0.0163	0.0340	0.0538
356.58	335	356.5714	356.5744	356.5727	29.29	R	1387.9153	1.030	1.897	0.1097	0.0205	0.0370	0.0507
600	3/9/37	356.5724	356.5725	0.0009	29.694	G	1389.2857	0.917	1.736	0.0962	0.0182	0.0338	0.0508
150	336	150.0020	150.0012	150.0016	29.15	R	934.6438	1.084	1.910	0.1042	0.0211	0.0371	0.0305
600	3/11/37	150.0047	149.9983	0.0018	29.625	G	935.5700	1.210	1.502	0.1072	0.0229	0.0303	0.0305
150	337	150.0026	150.0013	150.0016	29.17	R	934.6355	1.204	1.852	0.1250	0.0231	0.0364	0.0305
600	3/11/37	150.0045	149.9980	0.0020	29.624	G	935.5715	1.260	1.618	0.1067	0.0237	0.0321	0.0306
356.58	338	356.5803	356.5831	356.5815	29.17	R	1387.9135	1.104	1.940	0.0972	0.0218	0.0375	0.0504
600	3/12/37	356.5807	356.5819	0.0010	29.590	G	1389.2672	1.026	1.517	0.0865	0.0202	0.0306	0.0505
300	339	299.9934	299.9932	299.9930	29.19	R	1264.0202	1.041	1.914	0.0940	0.0204	0.0372	0.0437
600	3/12/37	299.9918	299.9937	0.0006	29.593	G	1265.2303	0.859	1.731	0.1010	0.0175	0.0337	0.0437

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
929.2961	-1	0.002964	29.0	29.0	28.93	29.542	0.0148	0.3289	1.2781	0.0034	-0.0088	930.912
930.1652	-1	0.002903	29.0	29.0	28.77	29.542	0.0162	0.2940	1.2647	0.0034	-0.0088	931.735
929.2949	-2	0.002964	29.0	29.0	29.01	29.537	0.0148	0.3307	1.2786	0.0034	-0.0088	930.914
930.1568	-1	0.002903	29.0	29.0	28.72	29.537	0.0162	0.2913	1.2638	0.0034	-0.0088	931.723
1571.1825	-1	0.002458	30.0	30.0	28.91	29.579	0.0003	1.3752	7.4055	0.0227	-0.0121	1579.974
1572.6345	-2	0.002286	31.2	30.0	29.08	29.579	0.0009	1.3130	7.3188	0.0224	-0.0121	1581.278
1571.1789	+1	0.002453	30.0	30.0	29.03	29.726	0.0002	1.3881	7.4162	0.0227	-0.0086	1579.998
1572.6695	0	0.002279	31.0	30.0	28.94	29.726	0.0007	1.3232	7.3280	0.0224	-0.0086	1581.335
929.3396	-2	0.002956	29.3	30.0	29.31	29.616	0.0147	0.3365	1.2779	0.0034	0.0062	930.978
930.2398	-2	0.002889	30.0	29.0	29.16	29.616	0.0160	0.2979	1.2632	0.0034	0.0062	931.826
929.3321	0	0.002955	29.7	30.0	29.29	29.642	0.0146	0.3247	1.2727	0.0034	0.0059	930.953
930.2094	-1	0.002888	30.0	29.5	29.15	29.642	0.0160	0.3220	1.2721	0.0034	0.0060	931.829
929.4055	0	0.002946	30.0	29.7	29.21	29.682	0.0145	0.3312	1.2747	0.0034	0.0004	931.030
930.3615	+1	0.002877	30.0	29.3	29.25	29.682	0.0159	0.2868	1.2569	0.0033	0.0004	931.925
929.3936	-1	0.002945	30.0	30.0	29.29	29.696	0.0145	0.3387	1.2770	0.0034	-0.0009	931.026
930.3444	+1	0.002877	30.0	29.7	29.22	29.696	0.0158	0.3032	1.2632	0.0033	-0.0009	931.929
1571.3531	-1	0.002460	30.2	30.0	29.29	29.758	0.0004	1.3814	7.4060	0.0226	-0.0044	1580.159
1572.9251	+2	0.002295	32.0	30.0	29.32	29.758	0.0011	1.3447	7.3564	0.0225	-0.0044	1581.645
1571.3469	+1	0.002460	30.0	30.0	29.31	29.690	0.0004	1.3802	7.4060	0.0226	-0.0031	1580.153
1572.9051	+2	0.002305	32.0	30.0	29.39	29.690	0.0014	1.3192	7.3249	0.0224	-0.0031	1581.570
929.3941	+1	0.002950	29.0	29.0	28.70	29.422	0.0145	0.3352	1.2815	0.0034	-0.0035	931.025
930.3159	+2	0.002882	29.0	29.0	28.39	29.422	0.0158	0.3176	1.2751	0.0034	-0.0035	931.924
929.3908	+1	0.002950	29.0	29.0	28.74	29.445	0.0146	0.3287	1.2786	0.0034	-0.0024	931.014
930.3196	+2	0.002882	29.0	29.0	28.52	29.445	0.0159	0.3158	1.2738	0.0034	-0.0024	931.926
1038.7465	-1	0.002836	29.0	29.0	29.07	29.610	0.0125	0.4682	2.0174	0.0057	-0.0033	1041.247
1039.7634	0	0.002743	30.0	29.0	29.00	29.610	0.0136	0.4495	2.0064	0.0056	-0.0033	1042.237
1474.5371	+3	0.002512	30.0	30.0	29.23	29.684	0.0027	1.1845	6.1966	0.0189	0.0002	1481.940
1475.9531	+5	0.002363	32.0	30.0	29.42	29.684	0.0036	1.1709	6.1797	0.0189	0.0002	1483.326
1380.1266	+2	0.002569	30.0	30.0	29.34	29.707	0.0049	1.0161	5.1280	0.0155	0.0161	1386.307
1381.4903	+3	0.002429	31.0	30.0	29.30	29.707	0.0059	0.9887	5.0997	0.0155	0.0161	1387.616
929.4019	-2	0.002952	29.0	30.0	29.25	29.608	0.0146	0.3325	1.2764	0.0034	-0.0035	931.025
930.3314	0	0.002883	30.0	29.2	29.14	29.608	0.0159	0.3026	1.2648	0.0034	-0.0035	931.915
929.3965	-3	0.002955	29.0	30.0	29.29	29.612	0.0147	0.3353	1.2776	0.0034	-0.0035	931.024
930.3322	0	0.002883	30.0	29.3	29.17	29.612	0.0156	0.3111	1.2680	0.0034	-0.0035	931.927
1380.1513	0	0.002571	29.0	29.5	29.16	29.558	0.0050	1.0141	5.1324	0.0155	-0.0033	1386.315
1381.5028	0	0.002430	30.0	29.0	28.93	29.558	0.0160	0.9599	5.0766	0.0154	-0.0033	1387.557
1256.9455	-2	0.002652	30.0	30.0	29.26	29.571	0.0077	0.7958	3.8626	0.0115	0.0154	1261.638
1258.1494	-2	0.002522	31.0	29.8	29.17	29.571	0.0087	0.7781	3.8472	0.0115	0.0154	1262.810

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TABLE XI (Continued)

t_r / p_o	Run No. / Date	t_b(310) / t_b(312)	t_b(313) / t_b(314)	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
250	340	250.0060	250.0081	250.0073	29.35	R	1154.4350	1.065	1.931	0.0985	0.0207	0.0374	0.0403
600	3/13/37	250.0054	250.0098	0.0016	29.666	G	1155.5683	1.039	1.738	0.0803	0.0213	0.0338	0.0403
150	341	150.0015	149.9997	150.0006	29.27	R	934.6547	1.152	1.914	0.1017	0.0222	0.0372	0.0307
600	3/15/37	150.0036	149.9975	0.0020	29.633	G	935.5757	1.189	1.740	0.1062	0.0226	0.0338	0.0307
150	342	150.0009	149.9992	150.0000	29.27	R	934.6392	1.186	1.881	0.1027	0.0228	0.0368	0.0307
600	3/15/37	150.0027	149.9970	0.0018	29.628	G	935.5675	1.246	1.751	0.1002	0.0235	0.0340	0.0307
400	343	399.9968	399.9974	399.9984	29.45	R	1482.8807	1.140	1.886	0.0957	0.0225	0.0368	0.0543
600	3/16/37	399.9989	400.0005	0.0013	29.687	G	1484.3080	0.998	1.806	0.0762	0.0198	0.0347	0.0544
356.58	344	356.5767	356.5773	356.5777	29.30	R	1387.9693	1.016	1.878	0.0908	0.0203	0.0367	0.0507
600	3/16/37	356.5764	356.5803	0.0013	29.700	G	1389.2763	0.871	1.760	0.0880	0.0174	0.0341	0.0508
200	345	200.0028	199.9982	200.0005	29.27	R	1044.6156	1.110	1.734	0.1055	0.0216	0.0348	0.0354
600	3/17/37	199.9991	200.0019	0.0018	29.629	G	1045.6236	1.022	1.761	0.0942	0.0207	0.0341	0.0354
150	346	150.0044	150.0028	150.0036	28.99	R	934.6492	1.114	1.918	0.1135	0.0216	0.0372	0.0303
600	3/18/37	150.0058	150.0016	0.0014	29.618	G	935.5662	1.176	1.706	0.1223	0.0224	0.0334	0.0303
150	347	150.0037	150.0021	150.0028	28.95	R	934.6535	1.189	1.897	0.1072	0.0229	0.0370	0.0302
600	3/18/37	149.9990	150.0065	0.0023	29.624	G	935.5785	1.220	1.754	0.0937	0.0231	0.0340	0.0302
250	348	250.0065	250.0086	250.0083	29.10	R	1154.4360	1.156	1.924	0.1017	0.0222	0.0373	0.0398
600	3/19/37	250.0062	250.0118	0.0019	29.667	G	1155.5257	1.112	1.813	0.1223	0.0227	0.0348	0.0399
356.58	349	356.5778	356.5800	356.5792	29.17	R	1387.9257	1.020	1.916	0.1092	0.0203	0.0372	0.0504
600	3/20/37	356.5774	356.5816	0.0016	29.683	G	1389.2412	0.794	1.817	0.1010	0.0160	0.0348	0.0505
300	350	300.0000	299.9984	299.9988	29.22	R	1264.0647	1.012	1.913	0.0932	0.0199	0.0372	0.0438
600	3/20/37	299.9958	300.0008	0.0016	29.657	G	1265.2463	0.941	1.793	0.1025	0.0191	0.0345	0.0438
150	351	150.0021	149.9998	150.0008	29.02	R	934.6477	1.117	1.909	0.1017	0.0216	0.0371	0.0303
600	3/22/37	150.0034	149.9978	0.0020	29.629	G	935.5578	1.134	1.804	0.1092	0.0217	0.0346	0.0303
150	352	150.0008	149.9985	149.9995	29.19	R	934.6362	1.186	1.902	0.1147	0.0228	0.0370	0.0305
600	3/22/37	149.9956	150.0031	0.0024	29.612	G	935.5522	1.221	1.806	0.1023	0.0231	0.0347	0.0306
444.6	353	444.6033	444.6057	444.6042	29.60	R	1580.2860	1.109	1.914	0.0945	0.0218	0.0372	0.0574
600	3/23/37	444.6042	444.6037	0.0007	29.717	G	1581.7590	1.112	1.837	0.0940	0.0222	0.0350	0.0574
444.6	354	444.6010	444.6005	444.6002	29.40	R	1580.2468	1.204	1.924	0.1003	0.0234	0.0373	0.0569
600	3/23/37	444.5995	444.5999	0.0005	29.691	G	1581.7415	1.176	1.824	0.0927	0.0233	0.0349	0.0570
150	355	150.0023	150.0001	150.0009	29.40	R	934.6623	1.128	1.954	0.0893	0.0218	0.0376	0.0308
600	3/25/37	150.0035	149.9978	0.0020	29.649	G	935.5652	1.184	1.330	0.0933	0.0225	0.0275	0.0309
150	356	150.0018	150.0009	150.0011	29.29	R	934.6385	1.210	1.869	0.1352	0.0232	0.0366	0.0307
600	3/25/37	149.9976	150.0041	0.0018	29.644	G	935.5480	1.233	1.607	0.1165	0.0233	0.0319	0.0307
150	357	150.0043	149.9999	150.0012	27.70	R	699.5345	1.169	1.852	0.1003	0.0221	0.0364	0.0213
450	4/1/37	150.0036	149.9972	0.0027	27.550	G	700.2402	1.239	1.538	0.1048	0.0249	0.0309	0.0214
150	358	150.0019	149.9972	149.9985	27.72	R	699.5192	1.143	1.826	0.1313	0.0217	0.0360	0.0214
450	4/1/37	150.0006	149.9944	0.0027	27.534	G	700.2278	1.232	1.587	1.1095	0.0247	0.0316	0.0214

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
1147.9575	-2	0.002744	29.8	30.0	29.40	29.673	0.0102	0.6253	2.8784	0.0084	-0.0161	1151.464
1149.0886	-2	0.002629	30.3	30.0	29.26	29.673	0.0113	0.5990	2.8593	0.0083	-0.0161	1152.550
929.4126	-1	0.002946	29.8	30.0	29.42	29.602	0.0145	0.3320	1.2750	0.0034	-0.0013	931.036
930.3322	0	0.002873	30.0	29.7	29.19	29.602	0.0158	0.3198	1.2706	0.0034	-0.0013	931.940
929.3990	0	0.002945	29.0	30.0	29.32	29.606	0.0145	0.3303	1.2747	0.0034	0.0000	931.022
930.3256	+1	0.002875	30.0	29.0	29.06	29.606	0.0158	0.3188	1.2710	0.0034	0.0000	931.935
1474.5644	+3	0.002510	30.0	30.0	29.45	29.659	0.0027	1.1833	6.1936	0.0189	0.0035	1481.966
1475.9831	+2	0.002352	32.0	30.0	29.59	29.659	0.0035	1.1592	6.1634	0.0188	0.0035	1483.332
1380.1789	0	0.002564	30.0	30.0	29.35	29.713	0.0048	1.0051	5.1155	0.0155	0.0051	1386.325
1381.4783	0	0.002415	31.0	30.0	29.44	29.713	0.0057	0.9870	5.0950	0.0154	0.0051	1387.586
1038.7621	0	0.002831	30.0	30.0	29.33	29.600	0.0123	0.4564	2.0083	0.0056	-0.0011	1041.244
1039.7643	0	0.002735	30.0	30.0	29.33	29.600	0.0135	0.4520	2.0054	0.0056	-0.0011	1042.240
929.4086	-2	0.002947	29.0	29.3	29.26	29.595	0.0146	0.3360	1.2779	0.0034	-0.0079	931.033
930.3251	0	0.002879	30.0	29.0	29.20	29.595	0.0159	0.3225	1.2725	0.0034	-0.0079	931.932
929.4133	-1	0.002947	29.0	29.7	29.20	29.604	0.0146	0.3327	1.2765	0.0034	-0.0062	931.034
930.3363	+1	0.002879	30.0	29.0	29.22	29.604	0.0159	0.3170	1.2701	0.0034	-0.0062	931.936
1147.9594	-2	0.002735	30.0	30.0	29.28	29.637	0.0100	0.6260	2.8790	0.0084	-0.0183	1151.464
1149.0461	+1	0.002621	31.0	30.0	29.47	29.637	0.0111	0.6218	2.8743	0.0084	-0.0183	1152.543
1380.1390	+2	0.002569	30.0	30.0	29.15	29.678	0.0049	1.0177	5.1318	0.0155	0.0018	1386.311
1381.4453	+2	0.002424	31.0	30.0	29.32	29.678	0.0058	0.9990	5.1106	0.0155	0.0018	1387.578
1256.9748	0	0.002653	30.0	30.0	29.34	29.644	0.0077	0.7956	3.8607	0.0115	0.0026	1261.653
1258.1517	+1	0.002518	31.0	30.0	29.49	29.644	0.0087	0.7848	3.8491	0.0115	0.0026	1262.808
929.4054	0	0.002952	29.5	29.8	29.32	29.600	0.0146	0.3318	1.2759	0.0034	-0.0018	931.029
930.3130	+1	0.002880	30.0	29.0	29.29	29.600	0.0159	0.3252	1.2732	0.0034	-0.0018	931.929
929.3983	-1	0.002948	29.3	29.7	29.37	29.588	0.0146	0.3354	1.2771	0.0034	0.0011	931.030
930.3119	0	0.002877	30.0	29.3	29.22	29.588	0.0158	0.3231	1.2724	0.0034	0.0011	931.928
1571.4143	-2	0.002458	30.3	30.0	29.64	29.739	0.0005	1.3728	7.3913	0.0226	-0.0093	1580.192
1572.8815	+1	0.002295	32.0	30.0	29.79	29.739	0.0013	1.3575	7.3707	0.0226	-0.0093	1581.624
1571.3837	-1	0.002458	30.0	30.0	29.44	29.718	0.0004	1.3771	7.3996	0.0226	-0.0004	1580.183
1572.8723	+2	0.002297	32.0	30.0	29.63	29.718	0.0012	1.3555	7.3700	0.0226	-0.0004	1581.621
929.4167	-1	0.002948	30.0	30.0	29.55	29.625	0.0146	0.3306	1.2739	0.0034	-0.0020	931.037
930.3254	+1	0.002877	30.0	30.0	29.53	29.625	0.0159	0.2846	1.2555	0.0033	-0.0020	931.883
929.3962	-1	0.002947	29.5	30.0	29.39	29.629	0.0145	0.3398	1.2781	0.0034	-0.0024	931.030
930.3054	+1	0.002876	30.0	29.7	29.21	29.629	0.0158	0.3135	1.2679	0.0034	-0.0024	931.904
695.8688	-1	0.002953	28.0	28.0	27.74	27.546	0.0108	0.2457	0.9747	0.0020	-0.0020	697.100
696.5791	-2	0.002876	28.2	28.0	27.46	27.546	0.0116	0.2284	0.9682	0.0019	-0.0020	697.787
695.8557	-1	0.002952	28.0	28.0	27.81	27.532	0.0108	0.2518	0.9771	0.0020	0.0025	697.100
696.5679	-2	0.002877	29.0	28.0	27.64	27.532	0.0116	0.2323	0.9693	0.0019	0.0025	697.786

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TABLE XI (Continued)

t_r / P_o	Run No. / Date	$t_b(310)$ / $t_b(312)$	$t_b(313)$ / $t_b(314)$	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(19)	(11)	(12)	(13)	(14)
444.6	359	444.6048	444.6039	444.6027	28.12	R	1182.5448	1.142	1.844	0.1123	0.0219	0.0363	0.0397
450	4/2/37	444.5985	444.6036	0.0021	27.567	G	1183.7410	1.095	1.322	0.1092	0.0222	0.0274	0.0397
444.6	360	444.6014	444.5972	444.5981	28.05	R	1182.5627	1.144	1.837	0.1012	0.0220	0.0362	0.0395
450	4/2/37	444.5942	444.5995	0.0024	27.567	G	1183.7453	1.101	1.340	0.1023	0.0223	0.0277	0.0396
150	361	150.0017	149.9982	149.9992	27.57	R	699.5315	1.157	1.738	0.0992	0.0219	0.0348	0.0212
450	4/5/37	150.0017	149.9952	0.0025	27.503	G	700.2207	1.235	1.271	0.1167	0.0248	0.0265	0.0212
150	362	150.0012	149.9978	149.9989	27.70	R	699.5257	1.154	1.880	0.1100	0.0219	0.0367	0.0213
450	4/5/37	150.0013	149.9953	0.0024	27.532	G	700.2233	1.221	1.657	0.0938	0.0246	0.0327	0.0214
444.6	363	444.6006	444.6006	444.5992	28.30	R	1182.5962	1.067	1.809	0.0917	0.0207	0.0358	0.0400
450	4/6/37	444.5966	444.5990	0.0014	27.655	G	1183.7553	1.021	1.418	0.0853	0.0209	0.0290	0.0401
444.6	364	444.5991	444.5972	444.5975	28.25	R	1182.5718	1.191	1.895	0.0982	0.0228	0.0369	0.0399
450	4/6/37	444.5957	444.5980	0.0010	27.658	G	1183.7420	1.182	1.576	0.0907	0.0238	0.0314	0.0400
150	365	150.0017	149.9973	149.9990	27.65	R	699.5440	1.113	1.843	0.0918	0.0212	0.0363	0.0213
450	4/8/37	150.0015	149.9955	0.0026	27.563	G	700.2217	1.122	1.448	0.1053	0.0228	0.0295	0.0213
150	366	150.0011	149.9970	149.9988	27.69	R	699.5393	1.210	1.843	0.0925	0.0228	0.0363	0.0213
450	4/8/37	150.0011	149.9958	0.0024	27.574	G	700.2230	1.254	1.675	0.0988	0.0251	0.0329	0.0214
400	367	400.0022	399.9997	400.0011	27.54	R	1109.6808	1.139	1.893	0.1018	0.0220	0.0369	0.0347
450	4/9/37	400.0020	400.0004	0.0010	27.472	G	1110.7577	1.066	1.587	0.0868	0.0221	0.0316	0.0348
356.58	368	356.5758	356.5765	356.5772	27.60	R	1038.6837	1.080	1.880	0.0947	0.0211	0.0367	0.0326
450	4/9/37	356.5771	356.5793	0.0011	27.503	G	1039.6635	0.990	1.596	0.1038	0.0201	0.0317	0.0326
200	369	200.0036	200.0009	200.0021	27.79	R	781.8350	0.997	1.883	0.0950	0.0192	0.0368	0.0236
450	4/10/37	200.0016	200.0024	0.0009	27.637	G	782.5972	1.082	1.727	0.0882	0.0215	0.0337	0.0236
150	370	150.0012	149.9964	149.9985	28.02	R	699.5582	1.185	1.838	0.0982	0.0224	0.0362	0.0217
450	4/12/37	150.0011	149.9952	0.0027	27.702	G	700.2303	1.217	1.470	0.1155	0.0245	0.0298	0.0217
150	371	150.0014	149.9969	149.9988	27.84	R	699.5462	1.209	1.776	0.0977	0.0227	0.0354	0.0215
450	4/12/37	150.0012	149.9959	0.0024	27.654	G	700.2265	1.279	1.666	0.0973	0.0255	0.0328	0.0215
356.58	372	356.5825	356.5852	356.5840	28.60	R	1038.7258	1.126	1.823	0.1107	0.0219	0.0360	0.0341
450	4/13/37	356.5817	356.5868	0.0020	27.743	G	1039.7240	1.090	1.540	0.1023	0.0219	0.0309	0.0342
300	373	299.9949	299.9939	299.9948	28.50	R	946.0220	1.091	1.890	0.1087	0.0212	0.0369	0.0302
450	4/13/37	299.9929	299.9974	0.0014	27.755	G	946.9462	1.086	1.498	0.0940	0.0210	0.0303	0.0302
250	374	250.0098	250.0102	250.0104	28.45	R	863.9970	1.050	1.912	0.1200	0.0203	0.0371	0.0267
450	4/14/37	250.0080	250.0136	0.0016	27.757	G	864.8380	1.061	1.563	0.0993	0.0205	0.0312	0.0267
150	375	150.0026	149.9961	149.9982	28.17	R	699.5542	1.104	1.898	0.1132	0.0211	0.0370	0.0218
450	4/15/37	150.0003	149.9940	0.0032	27.728	G	700.2357	1.147	1.654	0.1027	0.0232	0.0326	0.0219
150	376	150.0020	149.9960	149.9981	28.57	R	699.5642	1.165	1.846	0.1155	0.0220	0.0363	0.0222
450	4/15/37	150.0004	149.9941	0.0031	27.782	G	700.2387	1.217	1.695	0.1033	0.0245	0.0332	0.0223
200	377	200.0029	200.0006	200.0019	27.60	R	781.8157	1.086	1.780	0.1093	0.0208	0.0354	0.0234
450	4/16/37	200.0012	200.0028	0.0010	27.579	G	782.5717	1.109	1.722	0.0817	0.0220	0.0336	0.0234

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TABLE XI (Continued)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
1176.3577	-5	0.002457	29.0	29.0	28.09	27.577	-0.0001	1.0302	5.5950	0.0130	-0.0045	1182.991
1177.5568	-5	0.002269	31.0	28.7	27.87	27.577	0.0000	0.9746	5.5191	0.0128	-0.0045	1184.059
1176.3755	-2	0.002458	28.0	28.2	27.97	27.577	0.0000	1.0253	5.5904	0.0130	0.0031	1183.007
1177.5608	0	0.002288	29.2	28.0	27.84	27.577	0.0005	0.9741	5.5223	0.0128	0.0031	1184.074
695.8730	-1	0.002962	28.0	28.0	27.69	27.490	0.0109	0.2395	0.9733	0.0020	0.0013	697.100
696.5697	0	0.002893	28.0	28.0	27.60	27.490	0.0118	0.2153	0.9638	0.0019	0.0013	697.764
695.8618	0	0.002960	28.0	28.0	27.70	27.523	0.0108	0.2494	0.9769	0.0020	0.0018	697.103
696.5625	-1	0.002890	28.0	28.0	27.65	27.523	0.0118	0.2325	0.9703	0.0020	0.0018	697.781
1176.3897	-2	0.002458	28.8	29.0	28.24	27.703	0.0000	1.0191	5.5758	0.0129	0.0013	1182.999
1177.5498	0	0.002290	30.0	28.5	27.95	27.703	0.0005	0.9753	5.5197	0.0128	0.0013	1184.059
1176.3657	-1	0.002460	28.3	28.2	28.09	27.713	0.0001	1.0290	5.5917	0.0130	0.0041	1183.004
1177.5363	-1	0.002292	30.0	28.0	27.80	27.713	0.0005	0.9928	5.5455	0.0129	0.0041	1184.092
695.8758	0	0.002960	28.0	28.0	27.77	27.573	0.0108	0.2432	0.9739	0.0020	0.0016	697.107
696.5583	0	0.002891	29.0	28.0	27.74	27.573	0.0118	0.2234	0.9658	0.0019	0.0017	697.763
695.8713	0	0.002959	28.0	28.0	27.74	27.590	0.0108	0.2325	0.9738	0.0020	0.0020	697.103
696.5572	+1	0.002890	28.7	28.0	27.68	27.590	0.0118	0.2347	0.9704	0.0020	0.0020	697.778
1103.8900	-2	0.002517	28.0	28.0	27.49	27.452	0.0018	0.8895	4.6990	0.0109	-0.0018	1109.489
1104.9668	-2	0.002361	29.0	28.0	27.27	27.452	0.0024	0.8540	4.6578	0.0108	-0.0018	1110.490
1033.2561	-1	0.002572	28.0	28.0	27.58	27.490	0.0034	0.7550	3.8821	0.0089	0.0046	1037.910
1034.2347	0	0.002426	29.0	28.0	27.34	27.490	0.0041	0.7323	3.8592	0.0089	0.0046	1038.844
777.7239	+1	0.002841	28.0	28.0	27.86	27.653	0.0092	0.3480	1.5322	0.0033	-0.0035	779.613
778.4875	+1	0.002747	29.0	28.0	27.58	27.653	0.0100	0.3355	1.5257	0.0032	-0.0035	780.358
695.8741	0	0.002959	28.0	28.0	27.98	27.709	0.0109	0.2445	0.9727	0.0020	0.0025	697.107
696.5511	-1	0.002892	28.3	28.0	27.63	27.709	0.0118	0.2270	0.9666	0.0019	0.0025	697.761
695.8691	0	0.002959	28.0	28.0	27.84	27.666	0.0109	0.2412	0.9721	0.0020	0.0020	697.097
696.5512	0	0.002892	28.0	28.0	27.60	27.666	0.0118	0.2338	0.9698	0.0019	0.0020	697.770
1033.2560	0	0.002571	29.0	29.0	28.61	27.783	0.0035	0.7566	3.8717	0.0089	-0.0066	1037.890
1034.2541	+1	0.002428	31.0	29.0	28.67	27.783	0.0042	0.7273	3.8408	0.0088	-0.0066	1038.829
941.0347	-1	0.002653	29.0	29.0	28.48	27.795	0.0056	0.6000	2.9242	0.0066	0.0086	944.580
941.9604	+1	0.002527	30.0	29.0	28.45	27.795	0.0064	0.5640	2.8929	0.0065	0.0086	945.439
859.4385	-1	0.002744	29.0	29.0	28.40	27.787	0.0074	0.4742	2.1855	0.0048	-0.0171	862.093
860.2811	+1	0.002632	30.0	29.0	28.43	27.787	0.0083	0.4431	2.1628	0.0048	-0.0172	862.883
695.8648	0	0.002954	28.0	28.0	28.09	27.738	0.0108	0.2511	0.9746	0.0020	0.0030	697.106
696.5493	-1	0.002888	29.0	28.0	27.98	27.738	0.0118	0.2344	0.9683	0.0019	0.0030	697.769
695.8700	-1	0.002955	28.0	28.5	28.37	27.810	0.0109	0.2490	0.9724	0.0020	0.0031	697.107
696.5466	-2	0.002888	29.0	28.0	28.04	27.810	0.0118	0.2367	0.9686	0.0019	0.0031	697.769
777.7157	-2	0.002845	27.8	28.0	27.55	27.564	0.0092	0.3459	1.5332	0.0033	-0.0031	779.604
778.4707	0	0.002756	28.0	28.0	27.36	27.564	0.0101	0.3334	1.5268	0.0032	-0.0031	780.341

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TABLE XI (Continued)

t_r / p_o	Run No. / Date	$t_b(310)$ / $t_b(312)$	$t_b(313)$ / $t_b(314)$	t_b(ave.) / Ave. dev.	t_s / t_{Hg}	Bulb	H	h_1	h_2	h_3	δ_1	δ_2	δ_3
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
400	378	399.9986	399.9996	399.9999	28.22	R	1109.7148	1.171	1.870	0.1003	0.0225	0.0366	0.0359
450	4/17/37	400.0012	400.0003	0.0008	27.661	G	1110.7662	1.105	1.509	0.0878	0.0228	0.0304	0.0359
356.58	379	356.5750	356.5732	356.5737	28.05	R	1038.6738	1.130	1.883	0.1088	0.0220	0.0368	0.0333
450	4/17/37	356.5735	356.5732	0.0006	27.630	G	1039.6580	1.096	1.552	0.0917	0.0220	0.0311	0.0333
150	380	150.0024	149.9972	149.9995	28.20	R	699.5807	1.200	1.782	0.1117	0.0153	0.0354	0.0219
450	4/19/37	150.0021	149.9962	0.0028	27.765	G	700.2358	1.222	1.596	0.1017	0.0166	0.0317	0.0219
150	381	150.0012	149.9954	149.9980	27.94	R	699.5603	1.784	1.779	0.0945	0.0206	0.0354	0.0216
450	4/19/37	149.9932	150.0023	0.0037	27.719	G	700.2145	1.402	1.600	0.0992	0.0186	0.0318	0.0216
250	382	250.0026	250.0014	250.0024	28.35	R	863.9833	1.337	1.824	0.1130	0.0169	0.0360	0.0266
450	4/20/37	250.0002	250.0053	0.0016	27.742	G	864.7995	1.180	1.706	0.1027	0.0152	0.0334	0.0266
356.58	383	356.5753	356.5750	356.5752	27.74	R	1038.6555	1.496	1.870	0.1158	0.0186	0.0366	0.0328
450	4/21/37	356.5731	356.5774	0.0012	27.564	G	1039.6262	1.304	1.784	0.0990	0.0173	0.0344	0.0328
300	384	299.9966	299.9959	299.9967	27.62	R	945.9532	1.637	1.844	0.1280	0.0198	0.0363	0.0289
450	4/22/37	299.9950	299.9993	0.0013	27.531	G	946.8413	1.134	1.781	0.1132	0.0147	0.0344	0.0289
150	385	149.9995	149.9936	149.9962	27.60	R	699.5387	1.773	1.846	0.1112	0.0205	0.0363	0.0212
450	4/23/37	149.9991	149.9926	0.0031	27.565	G	700.1938	1.530	1.530	0.0922	0.0199	0.0308	0.0213
150	386	150.0005	149.9940	149.9969	27.70	R	699.5367	1.845	1.840	0.0957	0.0210	0.0362	0.0213
450	4/23/37	149.9999	149.9932	0.0033	27.577	G	700.1950	1.742	1.695	0.0900	0.0217	0.0332	0.0214
444.6	387	444.6056	444.6048	444.6050	27.94	R	1182.5560	1.496	1.727	0.1128	0.0185	0.0347	0.0394
450	4/24/37	444.6060	444.6038	0.0008	27.634	G	1183.6563	1.021	1.502	0.1030	0.0143	0.0303	0.0394
444.6	388	444.6065	444.6044	444.6048	28.23	R	1182.5883	1.616	1.652	0.1137	0.0195	0.0336	0.0395
450	4/24/37	444.6031	444.6050	0.0010	27.652	G	1183.6742	1.095	1.572	0.1098	0.0152	0.0314	0.0395
150	389	150.0010	149.9944	149.9977	27.74	R	699.5482	2.378	1.666	0.1092	0.0235	0.0338	0.0214
450	4/26/37	150.0008	149.9945	0.0032	27.677	G	700.2010	1.679	1.257	0.1140	0.0212	0.0262	0.0214
150	390	150.0008	149.9949	149.9977	28.12	R	699.5367	2.172	1.664	0.1112	0.0228	0.0338	0.0218
450	4/26/37	150.0005	149.9946	0.0030	27.614	G	700.1878	1.717	1.619	0.1008	0.0215	0.0321	0.0218
444.6	391	444.6033	444.6057	444.6033	28.20	R	1182.5523	1.557	1.825	0.1140	0.0190	0.0360	0.0398
450	4/27/37	444.6039	444.6004	0.0015	27.667	G	1183.6347	1.066	1.739	0.1132	0.0148	0.0338	0.0395
444.6	392	444.5995	444.6011	444.6002	28.17	R	1182.5550	1.410	1.748	0.1153	0.0177	0.0350	0.0398
450	4/27/37	444.6017	444.5986	0.0012	27.659	G	1183.6305	1.145	1.563	0.1067	0.0158	0.0312	0.0398
150	393	149.9995	149.9929	149.9959	28.12	R	699.5365	2.233	1.692	0.0993	0.0230	0.0342	0.0218
450	4/29/37	149.9986	149.9927	0.0031	27.655	G	700.1823	1.681	1.275	0.0982	0.0212	0.0266	0.0218
150	394	150.0007	149.9937	149.9968	27.97	R	699.5317	2.396	1.761	0.1115	0.0236	0.0352	0.0218
450	4/29/37	149.9994	149.9935	0.0032	27.633	G	700.1723	1.688	1.593	0.1080	0.0213	0.0317	0.0217

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TABLE XI (Concluded)

p'	$p'-p_e$	$\frac{1}{T_1}$	t_2	t_3	t_4	t_5	δ_4	δ_5	δ_6	δ_7	δ_8	p
(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
1103.8881	-2	0.002512	28.0	28.0	27.99	27.700	0.0018	0.8872	4.6873	0.0108	0.0002	1109.475
1104.9404	+1	0.002357	29.0	28.0	27.58	27.700	0.0024	0.8476	4.6422	0.0107	0.0002	1110.444
1033.2240	-2	0.002570	28.0	28.0	27.84	27.664	0.0035	0.7601	3.8830	0.0089	0.0104	1037.890
1034.2087	0	0.002423	29.0	28.0	27.56	27.664	0.0041	0.7244	3.8459	0.0088	0.0104	1038.802
695.8825	0	0.002955	28.0	28.0	28.01	27.772	0.0108	0.2449	0.0721	0.0020	0.0008	697.113
696.5391	0	0.002890	28.0	28.0	27.57	27.772	0.0118	0.2310	0.9678	0.0019	0.0008	697.752
695.8729	-1	0.002956	28.0	28.0	27.79	27.728	0.0108	0.2406	0.9713	0.0019	0.0033	697.101
696.5253	0	0.002890	28.0	28.0	27.48	27.728	0.0118	0.2307	0.9682	0.0019	0.0033	697.741
859.4248	0	0.002740	28.0	28.5	28.21	27.751	0.0074	0.4668	2.1813	0.0048	-0.0040	862.081
860.2376	+1	0.002630	29.2	28.2	28.07	27.751	0.0083	0.4537	2.1726	0.0048	-0.0040	862.873
1033.2144	-1	0.002571	28.0	28.0	27.67	27.543	0.0034	0.7617	3.8878	0.0089	0.0079	1037.884
1034.1809	-1	0.002429	28.8	28.0	27.50	27.543	0.0042	0.7455	3.8722	0.0089	0.0079	1038.820
941.0023	-1	0.002654	28.0	28.0	27.55	27.483	0.0055	0.6031	2.9369	0.0066	0.0054	944.560
941.8826	0	0.002530	28.5	28.0	27.35	27.483	0.0064	0.5908	2.9276	0.0066	0.0054	945.419
695.8695	0	0.002955	28.0	28.0	27.57	27.543	0.0108	0.2480	0.9762	0.0020	0.0063	697.113
696.5261	-2	0.002890	28.0	28.0	27.31	27.543	0.0118	0.2249	0.9678	0.0019	0.0063	697.739
695.8666	-1	0.002957	28.0	28.0	27.66	27.562	0.0108	0.2440	0.9743	0.0020	0.0051	697.103
696.5253	-2	0.002891	28.3	28.0	27.47	27.562	0.0118	0.2336	0.9708	0.0020	0.0051	697.749
1176.3525	0	0.002459	28.0	28.0	27.86	27.647	0.0001	1.0205	5.5832	0.0130	-0.0082	1182.961
1177.4472	+1	0.002289	29.5	28.0	27.61	27.647	0.0005	0.9906	5.5446	0.0129	-0.0083	1183.988
1176.3834	0	0.002459	28.2	28.5	28.05	27.680	0.0001	1.0140	5.5716	0.0129	-0.0079	1182.974
1177.4615	0	0.002291	30.0	28.2	27.80	27.680	0.0005	1.0000	5.5557	0.0129	-0.0079	1184.023
695.8705	-2	0.002954	27.8	28.0	27.72	27.674	0.0108	0.2380	0.9708	0.0019	0.0038	697.096
696.5251	-1	0.002892	28.0	28.0	27.46	27.674	0.0118	0.2138	0.9619	0.0019	0.0038	697.718
695.8667	-1	0.002954	28.0	28.0	27.99	27.615	0.0108	0.2384	0.9707	0.0019	0.0038	697.092
696.5147	0	0.002889	28.0	28.0	27.56	27.615	0.0118	0.2321	0.9694	0.0019	0.0038	697.734
1176.3414	0	0.002458	28.2	28.3	28.02	27.685	0.0000	1.0296	5.5932	0.0130	-0.0054	1182.972
1177.4162	+1	0.002289	30.0	28.2	27.78	27.685	0.0005	1.0168	5.5784	0.0130	-0.0054	1184.020
1176.3455	0	0.002458	28.0	28.0	27.95	27.692	0.0001	1.0234	5.5853	0.0130	-0.0003	1182.967
1177.4172	+1	0.002288	30.0	28.0	27.68	27.692	0.0004	0.9980	5.5528	0.0129	-0.0003	1183.981
695.8611	-1	0.002956	28.0	28.0	28.00	27.657	0.0108	0.2371	0.9699	0.0019	0.0068	697.088
696.5093	0	0.002891	28.3	28.0	27.57	27.657	0.0118	0.2112	0.9606	0.0019	0.0068	697.702
695.8585	-1	0.002954	28.0	28.0	27.91	27.634	0.0108	0.2437	0.9728	0.0020	0.0053	697.093
696.4970	-1	0.002890	28.0	28.0	27.49	27.634	0.0118	0.2323	0.9696	0.0019	0.0053	697.718

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TABLE XII

Spread of the Values of Certain Observed Quantities During the Series of Measurements

See Table XI. A = runs made in the oil thermostat: B = runs made in the nitrate thermostat.

p_0, mm. Hg	$t_r - t_b$ °C.	t_s °C.	t_{Hg} °C.	h_1 mm.	h_2 mm.	h_3 mm.
1000 A	-0.005 to +0.010	25.2 to 26.1	25.48 to 25.67	0.90 to 1.26	1.45 to 1.98	0.043 to 0.142
750 A	- .004 .004	25.3 27.0	25.40 25.71	1.02 1.31	1.23 1.92	.050 .152
600 A	- .009 .007	29.1 31.0	29.64 29.91	1.06 1.29	1.46 1.92	.060 .142
600 B	- .008 .012	28.6 30.1	29.46 29.72	0.80 1.26	1.33 1.96	.076 .135
450 A	- .007 .005	26.9 29.8	27.55 27.93	1.07 1.31	1.23 1.90	.054 .152
450 B	- .010 .006	27.5 28.6	27.47 27.78	0.99 1.84[a]	1.26 1.91	.082 .131
333 A	- .003 .002	29.3 30.9	29.69 29.88	1.13 1.44	1.64 1.93	.039 .139
333 B	- .040 .010	28.8 31.1	29.60 29.91	1.05 1.40	1.34 1.95	.066 .143

p_0, mm. Hg	$p' - p_e$ mm. Hg	t_2 °C.	t_3 °C.	t_4 °C.	t_5 °C.
1000 A	-6 to +10	25.0 to 32.0	25.0 to 27.5	25.0 to 26.2	25.44 to 25.68
750 A	-5[b] 3	25.0 37.0	25.0 32.0	25.2 26.9	25.37 25.75
600 A	-6 3	28.5 35.3	29.0 32.8	28.8 31.1	29.60 29.93
600 B	-4 5	29.0 32.0	29.0 31.0	28.4 30.2	29.42 29.76
450 A	-4 2	26.0 34.0	27.0 31.3	26.9 29.7	27.53 27.96
450 B	-5 1	27.8 31.0	28.0 29.0	27.3 28.7	27.45 27.81
333 A	-4 3	29.0 32.0	29.0 32.5	29.0 30.8	29.68 29.88
333 B	-12 4[c]	29.0 35.0	29.0 31.7	28.6 31.2	29.58 29.94

During the calibration of V_5 average h_2 was 1.55 mm. (spread 1.32 to 1.73); average h_3 was 0.095 mm. (spread 0.071 to 0.107).

[a]Over 2 mm. for Runs 389R, 390R, 393R, 394R. [b]About -100 mm. for Runs 160 and 161. [c]About + 100 mm. for Run 305.

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TABLE XIII

Values of the Individual Correction Terms for an Ice-Point Pressure of Approximately 600 Millimeters of Mercury

See Tables VI to IX and Table XI.

Correction	Equations		
	b	$i (i = 1,2,3,4,5)$	
δ_4	$3.3045 \times 10^{-5} \frac{p' V_b l_b}{V T_b}$	$3.3045 \times 10^{-5} \frac{p' V_b l_i}{V T_i}$	
δ_5	$\frac{p'}{V}(V_b - V_{bn})$	$\frac{p'}{V}(V_i - V_{in})$	($i = 1$ missing)
δ_6		$\frac{p'}{V} V_i \left(\frac{T_b}{T_i} - 1\right)$	(for $i = 1$ use V_1)
$\delta_{7.1}$	$\frac{p'^2}{RV} B_r \left(\frac{V_b - V}{T_r}\right)$	$\frac{p'^2}{RV} B_r \frac{2V_i}{T_i}$	(for $i = 1$ use V_1)
$\delta_{7.2}$		$-\frac{p'^2}{RV} T_r \frac{B_i V_i}{T_i^2}$	(for $i = 1$ use V_1)

Corr. / Space	b	1	2	3	4	5	Total
Correction in standard millimeters of mercury							
Run 200 Red at 0° C.							
δ_4	+0.01663	+0.03281	+0.01026	+0.01392	-0.03139	-0.01605	+0.0262
δ_5	+ .00030		+ .00001	+ .00001	+ .00005	+ .07316	+ .0735
δ_6		- .00609	- .00359	- .00692	- .04519	- .13919	- .2010
$\delta_{7.1}$	+ .00075	- .00008	- .00002	- .00005	- .00031	- .00094	
$\delta_{7.2}$		+ .00003	.00000	+ .00001	+ .00006	+ .00018	
δ_7	+ .00075	- .00005	- .00002	- .00004	- .00025	- .00076	- .0004
Run 202 Red at 202 Red at 100° C.							
δ_4	+0.01662	+0.03813	+0.01372	+0.01879	-0.04292	-0.02192	+0.0224
δ_5	+ .12298		+ .00002	+ .00002	+ .00007	+ .08929	+ .2124
δ_6		+ .01709	+ .01072	+ .02175	+ .14841	+ .44830	+ .6463
$\delta_{7.1}$	- .00058	+ .00008	+ .00003	+ .00005	+ .00034	+ .00104	
$\delta_{7.2}$		- .00001	+ .00001	+ .00002	+ .00015	+ .00045	
δ_7	- .00058	+ .00007	+ .00004	+ .00007	+ .00049	+ .00149	+ .0016
Run 323 Red at 444.6° C.							
δ_4	+0.01660	+0.06087	+0.02682	+0.03638	-0.09831	-0.04209	+0.0003
δ_5	+1.19432		+ .00002	+ .00002	+0.00011	+0.18075	+1.3752
δ_6		+ .24154	+ .13418	+ .25857	+1.68212	+5.08910	+7.4055
$\delta_{7.1}$	- .00354	+ .00095	+ .00040	+ .00076	+0.00494	+0.01497	
$\delta_{7.2}$		- .00034	+ .00008	+ .00016	+0.00109	+0.00319	
δ_7	- .00354	+ .00061	+ .00048	+ .00092	+0.00603	+0.01816	+0.0227

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TABLE XIV

Errors in δ_4, δ_6, and δ_7 Caused by Errors in the Assumed Kelvin Temperature

T = Kelvin temperature resulting from the present investigation.
T_a = Kelvin temperature used in computing δ_4, δ_6, and δ_7; see Table II-7.

t, °C. (Int.)	$T - T_a$, °C.	t, °C. (Int.)	$T - T_a$, °C.
0	+0.005	200	+0.024
25	.001	250	.038
50	.000	300	.048
75	.002	356.58	.057
100	.005	400	.062
150	.013	444.6	.056

Run \ Correction	δ_4	δ_6	δ_7	Total
Error in units of 10^4 standard mm. of mercury caused by above errors in T				
200 Red at 0°C.	0.0	+0.3	0.0	+0.3
202 Red at 100°C.	0.0	+0.4	0.0	+0.4
323 Red at 444.6°C.	0.0	+9.5	0.0	+9.5

Approximate ice-point pressure of above runs = 600 mm.

TABLE XV

Error in H for Run 323 R

See Eq. (1).

Observed quantity	Probable error in observed quantity	10^4 x Probable error in H	Observed quantity	Probable error in observed quantity	10^4 x Probable error in H
M_1	0.001 mm.	10 mm.	S_2	0.001 mm.	10 mm.
M_2	0.001 mm.	10	m	0.5%	10
S_1	0.001 mm.	10	optical	errors	25

Total probable error in H is 33.5 x 10^{-4} mm.

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TABLE XVI

Error in p' for Run 323 R

See Table IV.

Observed quantity	Probable error in observed quantity	10^4 x Probable error in p'	Observed quantity	Probable error in observed quantity	10^4 x Probable error in p'
1. Errors in Observed Quantities					
H	0.00335 mm.	33.3 mm.	ϵ_1	0.001 mm.	9.9 mm.
h_1	.005 mm.	0.8	ϵ_2	.001 mm.	9.9
h_2	.005 mm.	0.6	t_s	.1°C.	2.4
d_1	.1 mm.	6.0	t_{Hg}	.01°C.	28.4
d_2	.01 mm.	0.9	g_l	--	--
2. Errors in Properties of Materials					
a_{Hg}	1%	8.0 mm.	β_{Hg}	10%	3.4 mm.
α_s	10%(3.5°C.)	8.2	α_{Hg}	0.05%(0.5°C.)	0.7
$\rho_s g_l / 2E_s$	10%	0.8			

Total probable error in p' is 47.9 x 10^{-4} standard mm. of mercury.

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TABLE XVII

Error in p for Run 323 R

See Tables VI to X.

Observed quantity	Probable error in observed quantity	10^4 x Probable error in in p	Observed quantity	Probable error in observed quantity	10^4 x Probable error in in p
1. Errors in Observed Quantities					
l_{bn}	0.1 mm.	0.1 mm.	t_b	0.002°C.	43.7 mm.
l_{1n}	0.1 mm.	0.1	t_1	0.5°C.	7.6
l_{2n}	0.1 mm.	0.2	t_2	0.5°C.	4.2
l_{3n}	0.1 mm.	0.2	t_3	0.5°C.	8.0
l_{4n}	0.1 mm.	0.2	t_4	0.1°C.	9.2
l_{5n}	0.1 mm.	0.2	t_5	0.01°C.	2.9
V_{bn}	0.1 ml.	0.8	d_2	0.1 mm.	0.5
V_{1n}	0.001 ml.	12.1	h_2	0.005 mm.	12.6
V_{2n}	0.001 ml.	21.7	h_3	0.002 mm.	25.7
V_{3n}	0.001 ml.	21.7	p'	0.005 mm.	50.3
V_{4n}	0.001 ml.	21.8	$p' - p_e$	0.5 mm.	0.5
V_{5n}	0.001 ml.	21.8			
2. Errors in Properties of Materials					
α_b	0.5%	60.0	α_1	1%	0.1
$\alpha_{b'}$	0.5%	0.0	a_{Hg}	1%	67.7
β_b	2.5%	1.0	B	2%(t_b), 10%(t_1)	7.9
γ_b	0.5%	0.0	α_v	0.1%	0.1

3. Constant Errors

Source of error	$10^4 \times \Delta p$
Stretch of dead spaces with variations in p'	+ 3.1 mm.
Use of α_b for graded seal	+ 9.9
Temperature scale employed (see Table XIV)	+ 9.5
Formulas	- 4.8

Total probable error in p is 128.2 x 10^{-4} standard mm. of mercury

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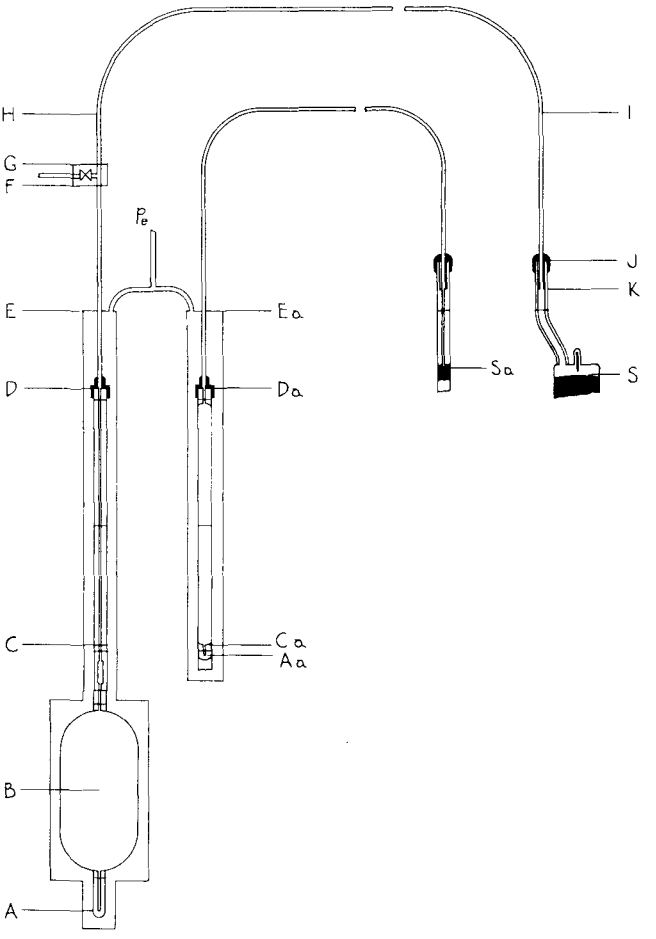

Figure 1.--Sketch of one of the thermometer systems.

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Proceedings of the American Academy of Arts and Sciences

VOL. 77, No. 9, P. 341–372—JULY, 1949

SUMMER NUMBER

RECORDS OF MEETINGS
FROM OCTOBER 1948 TO MAY 1949

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Numbers 8 and 9 of Volume 77 were printed at different plants. Because of a last minute change in the arrangement of the tables in Number 8 that number ends with page 336 instead of 340 as had been originally planned. It was impossible to change the page numbering of Number 9 to conform.

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RECORDS OF MEETINGS

October 13, 1948—Stated Meeting

The One Thousand Three Hundred and Twenty-eighth Meeting of the Academy convened in its House on October 13, 1948, and was called to order by the President at 8:24 P. M.

There were present sixty-five Fellows, one Foreign Honorary Member, and thirty-four guests.

The records of the meeting of May 12, 1948, were read and approved.

The President reiterated the cordial standing invitation to all gentlemen and ladies who are interested in the communications of our stated meetings, and the welcome which the Academy extends to personal guests of Fellows to join also in the informal social gatherings and refreshments in the reading room.

Recently elected Fellows were introduced as follows: Bartlett Harding Hayes, Jr., IV: 4, by Mr. Jones; Charles DuBois Coryell, I: 3, by Mr. Scatchard; Edwin Richard Gilliland, I: 4, Thomas Kilgore Sherwood, I: 4, by Mr. Moreland; Bishop Carleton Hunt, III: 3, by Mr. Usher; William Ted Martin, I: 1, by Mr. Phillips; Victor Frederick Weisskopf, I: 2, by Mr. Slater; George Wald, II: 3, by Mr. Hisaw; Oscar Zariski, I: 1, by Mr. Birkhoff; Rudolph Florin (F. H. M.), II: 2, by Mr. Bailey; Robert Burns Woodward, I: 3, by Mr. Land.

Introduced by Mr. Schmitt on behalf of the Rumford Committee, as a recently elected Fellow, and also the Rumford medallist for 1947, Edmund Newton Harvey, II: 3, received at the hand of the President the Rumford gold and silver medals for his fundamental investigations of the nature of bioluminescence, an interesting résumé of which was presented by the medallist under the title of *The Nature of Animal Light,* to an appreciative audience which by questions showed an extensive and varied interest in the still unsolved Luciferin-Luciferase reaction of biological luminescence.

The meeting was dissolved at 9:48 P. M.

November 10, 1948—Stated Meeting

The One Thousand Three Hundred and Twenty-ninth Meeting of the Academy convened in its House on November 10, 1948, and was called to order by the President at 8:15 P. M.

There were present fifty-two Fellows and twenty-one guests.

The records of the meeting of October 13 were read and approved.

The Secretary announced that the Council took the following action at its meeting this evening: It was voted to discharge with

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thanks the Committee on UNESCO and to replace it with a new Committee on International Relations: this committee to insert in appropriate journals our invitation to foreign scholars to use the House of the Academy as headquarters, and to extend such hospitality to them as is permitted by current appropriation.

The President announced the A. D. Little Memorial Lecture by Robert E. Wilson at the Massachusetts Institute of Technology, on November 23.

Recently elected Fellows were introduced as follows: Erwin Dain Canham, III: 4, by Mr. Caldwell; Frederick May Eliot, IV: 1, by Mr. Sperry; Carl Tilden Keller, III: 4, by Mr. J. D. M. Ford; Robert Cutler, III: 4, Francis Calley Gray, II: 4, Bruno Benedetto Rossi, I: 2, by Mr. Killian; Ivan Alexander Getting, I: 4, by Mr. Bunker; Herbert John Davis, III: 4, by Mr. Jones.

The following communication was presented:

W. L. Sperry: *The Present Outlook for Religion.*

The meeting was dissolved at 9:30 P. M.

December 8, 1948—Stated Meeting

The One Thousand Three Hundred and Thirtieth Meeting of the Academy convened in its House on December 8, 1948, and was called to order by the President at 8:25 P. M.

There were present forty-two Fellows and sixty-three guests.

The records of the meeting of November 10 were read and approved.

The Secretary announced that the Council took the following action at its meeting this evening: (1) Approval of the presidential appointment of a special Committee on International Relations as follows: I. Amdur, Chairman, W. G. Constable, Hudson Hoagland, W. G. Leland, W. T. Martin; (2) Approval of the appointment of Mr. Amdur as the Academy's representative in the Division of International Relations of the National Research Council; (3) Approval of grants from the Rumford Fund to Otto Glaser, Amherst College, $250; and R. F. Daubenmire, State College of Washington, $500.

The Secretary announced that for Ladies' Night at the stated March meeting Samuel Chamberlain will demonstrate the art of dry point etching.

Mr. Amdur, Chairman of the Committee on International Relations, reported on a communication received by the Secretary from the Committee on International Exchange of Persons of the Conference Board of Associated Research Councils concerning opportunities under the Fulbright Act of the United States Congress.

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The President announced that an acoustics exhibit will be in the lobby of the House from December 17 to January 2.

Recently elected Fellows were introduced as follows: Dr. John Rock, II: 4, and Dr. Allan Macy Butler, II: 4, by Dr. Janeway.

The Academy's Francis Amory Prizes for the Septennium ending November 10, 1947, were presented by the President and Mr. Edwin B. Wilson, Chairman of the Amory Prize Committee. A cash prize of $3,500 was awarded, together with a diploma to each of the following: Alexander Benjamin Gutman, M.D., of New York City; Charles Brenton Huggins, M.D., of Chicago; Willem Johan Kolff, of Kampen, Holland; Guy Frederick Marrian, of Edinburgh; George Nicholas Papanicolaou, M.D., of New York City; Selman Abraham Waksman, of New Brunswick, New Jersey.

Dr. Marrian, who was unable to be present in person, was represented by Charles Eric Whitamore, British Consul General at Boston.

The following communication was presented:

C. B. Huggins: *Medical Significance of the Amory Prize Researches.*

The meeting was dissolved at 9:20 P. M.

January 12, 1949—Stated Meeting

The One Thousand Three Hundred and Thirty-first Meeting of the Academy convened in its House on January 12, 1949, and was called to order by the President at 8:27 P. M.

There were present thirty-nine Fellows and twenty-six guests.

The records of the meeting of December 8 were read and approved.

The Secretary distributed a list of the following sixty-five Fellows who have accepted election since May, 1948: Richard Bissell, Jr. (III: 3); Francis Gilman Blake (II: 4); Bernard Bloch (IV: 3); Arthur Francis Buddington (II: 1); Allan Macy Butler (II: 4); Erwin Dain Canham (III: 4); Rudolph Carnap (IV: 1); Edward Sears Castle (II: 2); Yuen Ren Chao (IV: 3); John Chipman (I: 4); Edward Delos Churchill (II: 4); William Lockhart Clayton (III: 2); Charles Woolsey Cole (III: 4); Charles Allerton Coolidge (III: 1); Carl Ferdinand Cori (I: 3); Charles DuBois Coryell (I: 3); Robert Cutler (III: 4); Herbert John Davis (III: 4); Edward Adelbert Doisy (II: 3); Frederick May Eliot (IV: 1); Carl Stephens Ell (III: 4); Wallace Osgood Fenn (II: 3); Herbert Spencer Gasser (II: 3); Ivan Alexander Getting (I: 4); Edwin Richard Gilliland (I: 4); Francis Calley Gray (III: 4); Edmund Newton Harvey (II: 3); Bartlett Harding Hayes, Jr. (IV: 4); Hoyt Clarke Hottel (I: 4); Bishop Carleton Hunt (III: 3); Theodore von Kármán (I: 4); Carl Tilden Keller (III: 4); Adolph Knopf (II: 1) David Eli Lilienthal (III: 4); William Henry McAdams (I: 4); John

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Marin (IV: 4); William Ted Martin (I: 1); Margaret Mead (IV: 2); Thomas Munro (IV: 4); Arthur Edward Murphy (IV: 1); Erwin Panofsky (IV: 4); Hans Reichenbach (IV: 1); William Jacob Robbins (II: 2); John Rock (II: 4); Bruno Benedetto Rossi (I: 2); Julian Seymour Schwinger (I: 2); Thomas Kilgore Sherwood (I: 4); Bruce Simonds (IV: 4); George Gaylord Simpson (II: 1); Alfred Pritchard Sloan, Jr. (III: 4); John Sloan (IV: 4); Alfred Tarski (IV: 1); William Randolph Taylor (II: 2); Berthold Louis Ullman (IV: 3); Hubert Bradford Vickery (II: 3); Vincent du Vigneaud (I: 3); George Wald (II: 3); Victor Frederick Weisskopf (I: 2); Frits Warmolt Went (II: 2); Walter Gordon Whitman (I: 4); Howard Eugene Wilson (III: 2); Robert Burns Woodward (I: 4); Sewall Wright (II: 3); Henry Merritt Wriston (III: 4); Oscar Zariski (I: 1); and the following twelve Foreign Honorary Members: José d'Almada (III: 2); Charles Herbert Best (II: 3); P. Boysen-Jensen (II: 2); Jean-Marie Carré (IV: 4); Archibald Gowanlock Huntsman (II: 3); Max von Laue (I: 2); Léon Julliot de la Morandière (III: 1); Sir Robert Robinson (I: 3); Birbal Sahni (II: 2); Jan Hendrik Scholte (IV: 4); Arnold Sommerfeld (I: 2); The Svedberg (I: 3). This makes the total current membership 802 Fellows, forty-one Fellows Emeriti, and 127 Foreign Honorary Members.

The Secretary announced that the Council took the following action at its meeting this evening: (1) Acceptance of the recommendation of the Permanent Science Fund Committee for a grant of $11,750 to Norman J. Padelford, Professor of International Relations, Massachusetts Institute of Technology; (2) Approval by the Council that the Secretary and Treasurer should prepare a proposed amendment to the Academy's charter to remove the ceilings limiting the amounts of personal and real property that may be held by the Academy.

Newly elected Fellows were introduced as follows: John Chipman, I: 4, by Mr. Williams; Charles Allerton Coolidge, III: 1, by Mr. Lowell; Hoyt Clarke Hottel, I: 4, and Walter Gordon Whitman, I: 4, by Mr. W. K. Lewis.

The following communication was presented:

A. E. Goldschmidt: *Resources and Resourcefulness.*

The meeting was dissolved at 9:45 P. M.

February 9, 1949—Stated Meeting

The One Thousand Three Hundred and Thirty-second Meeting of the Academy convened in its House on February 9, 1949, and was called to order by the President at 8:19 P. M.

There were present fifty-six Fellows and seventy-nine guests.

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The records of the meeting of January 12 were read and approved.

The Secretary announced that the Council desires to call to the attention of the Fellows that at the stated March meeting of the Academy a vote will be taken on a proposal to amend the Statutes, Chapter XI, Article 1, par. iii, to increase the membership of the Committee on Meetings by adding the four vice-presidents, *ex officiis*.

The Secretary reported that the Council has recommended, subject to final legal advice, the following petition for amending the Academy's Charter to the General Court in order to remove the limitations on the amount of property that the Academy may hold:

> "*Section 1.* Section 6 of Chapter 46 of the Acts of 1779, as amended by Section 2 of Chapter 129 of the acts of 1910 and by Section 2 of Chapter 47 of the acts of 1911, is hereby further amended by striking out the words following the first semicolon, so that said section shall read as follows:— Section 6. That the Fellows of the said Academy may and shall forever hereafter be deemed capable in the law of having, holding, and taking in fee simple or any less estate, by gift, grant, devise, or otherwise, any lands, tenements, or other estate, real and personal."

Recently elected Fellows were introduced as follows: Julian Seymour Schwinger, I: 2, by Mr. Kemble; Henry Merritt Wriston, III: 4, by Mr. Carmichael.

The following communication was presented:

Robert F. Bacher: *The Development of Nuclear Reactors.*

The meeting was dissolved at 9:35 P. M.

March 9, 1949—Stated Meeting

The One Thousand Three Hundred and Thirty-third Meeting of the Academy convened in its House on March 9, 1949; and, in the absence of the President, was called to order by Vice-President Jackson at 8:25 P. M.

This meeting had been designated as Ladies' Night, and there were present fifty-seven Fellows and seventy-eight guests.

The records of the meeting of February 9 were read and approved.

It was voted to amend the Statutes, Chapter XI, Article 1, par. iii, to read as follows: "The Committee on Meetings shall consist of the President as Chairman, the Secretary, *ex officio*, who shall be secretary of the committee, the four Vice-Presidents, *ex officiis*, and of four other Fellows, not members of the Council, one from each Class. It shall arrange for meetings of the Academy."

The Secretary announced that the Council took the following action at its meeting this evening: (1) Voted to release the Secretary from the mandate to seek legislative action to alter the charter, in view of

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the fact that a Massachusetts statute (Chapter 180, s. 9) automatically removes the limitation indicated in our charter and makes the limit of property that may be held $5,000,000; (2) Approved five grants from the Permanent Science Fund; (3) Approved the recommendation of the Rumford Committee to award the Rumford Premium for 1949 to Dr. Ira S. Bowen, Director of the Mount Wilson and Palomar Observatories in California.

Vice-President Jackson announced that the President had appointed the following Nominating Committee: Edwin H. Land of Class I; Samuel A. Levine of Class II; Abbott P. Usher of Class III (Chairman); and Bartlett H. Hayes, Jr. of Class IV.

The following communication was presented:

Samuel Chamberlain: *A Demonstration of the Technique of Dry Point.*

The meeting was dissolved at 9:50 P. M.

April 13, 1949—Stated Meeting

The One Thousand Three Hundred and Thirty-fourth Meeting of the Academy convened in its House on April 13, 1949, and was called to order by the President at 8:20 P. M.

There were present thirty-nine Fellows, one Foreign Honorary Member, and sixty guests.

The records of the meeting of March 9 were read and approved.

On the recommendation of the Council, the annual assessment of $15 for 1949–1950 and the following appropriations were voted:

For General Administration and Meetings	$ 4,150
For Salaries and Pensions	13,497
For House Maintenance (including alterations)	6,135
For President's Expense	600
For Treasurer's Expense	700
For Committee on International Relations (Balance cont.)	150
For World Congress of Mathematicians (Balance cont.)	1,000
Amory Fund	100
Permanent Science Fund	65,000
Publication Committee	8,000
Rumford Fund Committee	5,000
School Science Fund (Balance cont.)	1,813
Warren Fund Committee	1,500

The Secretary announced that the Council approved four grants-in-aid from the Rumford Fund at its meeting this evening.

The following communication was presented:

Sir Harold Spencer Jones: *The Measurement of Time.*

The meeting was dissolved at 10:00 P. M.

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May 11, 1949—Annual Meeting

The One Thousand Three Hundred and Thirty-fifth Meeting of the Academy convened in its House on May 11, 1949, and was called to order by the President at 8:20 P. M.

There were present thirty Fellows and ten guests.

The records of the meeting of April 13 were read and approved.

The Secretary read the following report on deaths, resignations, and the status of the membership:

I regret to have to report the following deaths: Twenty Fellows and one Fellow Emeritus—James Rowland Angell (IV: 1), Henry Moore Bates (III: 1), Ruth Fulton Benedict (IV: 2), Robert Johnson Bonner (IV: 3), William Brooks Cabot (IV: 2), Joseph Augustine Cushman (II: 3), Tenney Lombard Davis (I: 3), Frank Albert Fetter (III: 3), James Geddes (FE IV: 3), Charles Grove Haines (III: 2), Charles Evans Hughes (III: 1), Robert Tracy Jackson (II: 1), Ernest George Merritt (I: 2), Harry Alvin Millis (III: 3), Wesley Clair Mitchell (III: 3), Rudolph Schevill (IV: 3), Richard Pearson Strong (II: 4), John Strong Perry Tatlock (IV: 3), Frederick John Teggart (III: 3), Richard Chace Tolman (I: 3), Bailey Willis (II: 1); Five Foreign Honorary Members—Alfredo Casella (IV: 4), Mircea Djuvara (III: 1), Augustus Daniel Imms (II: 3), Birbal Sahni (II: 2), Sir D'Arcy Wentworth Thompson (II: 3).

Four Fellows have resigned: Walter Sydney Adams (I: 1), Clarence Crane Brinton (IV: 2), Samuel Foster Damon (IV: 4), Thomas Head Thomas (III: 2).

Nine Fellows have been classed as Emeriti: Thorne Martin Carpenter (II: 3), Sterling Price Fergusson (II: 1), George Shannon Forbes (I: 3), William Henry Paine Hatch (IV: 1), Henry Wyman Holmes (III: 3), Ralph Restieaux Lawrence (I: 4), Elmer Drew Merrill (II: 2), William Hoyt Worrell (IV: 3), Charles Henry Conrad Wright (IV: 4).

In May, 1948, seventy-one Fellows and thirteen Foreign Honorary Members were elected to the Academy; all except six Fellows (Leonard Bloomfield, Dwight David Eisenhower, Enrico Fermi, Paul Gray Hoffman, Edward Hopper, Hassler Whitney) and one Foreign Honorary Member (Diego Rivera) accepted election.

The roll now includes 790 Fellows, 44 Fellows Emeriti, and 124 Foreign Honorary Members (exclusive of those elected in 1949).

The following annual reports were read and approved:

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REPORT OF THE TREASURER

(Extract)

RECEIPTS*

Academy, General:			
Investment Income	$34,842.43		
Less: Income to Special Funds	15,112.35		
		$19,730.08	
House Charges and Equipment Sales		3,920.19	
Assessments and Admission Fees		7,050.00	
			$30,700.27
Mabel S. Agassiz Fund:			
Investment Income			112.00
Amory Fund Committee:			
Investment Income			3,886.79
Kennelly Fund:			
Investment Income			87.92
Life Membership Fund:			
From Ivan A. Getting and Hoyt C. Hottel			400.00
Permanent Science Fund:			
Boston Safe Deposit and Trust Co., Trustee		$11,042.95	
Return of Grant		46.96	
Investment Income		2,912.00	
			14,001.91
Publications Committee:			
Investment Income		$2,849.67	
Sale of Publications		2,634.78	
Lake Publications		264.27	
			5,748.72
Rumford Fund Committee:			
Investment Income		$4,233.29	
Sale of Publications		10.77	
			4,244.06
School Science Fund:			
Contributions		$300.00	
Permanent Science Fund		2,500.00	
			2,800.00
Special House Alterations Fund:			
Sales, Harvard University			1,012.00
Warren Fund Committee:			
Investment Income			1,030.68
Total Receipts			$64,024.35

*Excluding sales of securities.

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EXPENDITURES*

Academy, General:			
Salaries and Pensions		$10,397.14	
Meetings and General Administration		5,581.38	
House Maintenance		6,499.91	
President's Expense		472.84	
Treasurer's Expense		703.99	
Special Appropriations:			
Alterations	$12,929.51		
Less: 1948 Appropriation Balance and Sales to Harvard University	5,449.22		
		7,480.29	
Unesco Committee Special		60.87	
			$31,196.42
Mabel S. Agassiz Fund:			
For Meetings			112.00
Amory Fund:			
Awards		$21,000.00	
Expense		1,033.47	
			22,033.47
Permanent Science Fund:			
Grants		$12,950.00	
Expense		48.15	
			12,998.15
Publications Committee:			
Bulletin		$ 1,104.13	
Proceedings		6,238.24	
Miscellaneous		72.68	
			7,415.05
Rumford Fund Committee:			
Grants		$ 1,150.00	
Expense		86.41	
			1,236.41
School Science Fund			1,846.70
Warren Fund Committee:			
Grants			725.00
Total Expenditures			$77,563.20

Respectfully submitted,

HORACE S. FORD, *Treasurer*

May 11, 1949

* Excluding purchases of securities.

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REPORT OF THE HOUSE COMMITTEE

During the past year the roof was re-covered for the first time since the House was built in 1912, although there had been minor repairs to stop previous leaks. Other major repairs and alterations during the year included a new roof and weatherproofing of the sidewalls of the library-stack wing; on the fourth floor, new lighting fixtures and paint to make office space in the northern corner, and an acoustic-tile ceiling and an additional radiator in both offices; new drapes and fixtures over the windows of the Lecture Hall; and new electric circuits to provide ample current to the exhibit space in the lobby.

This is the fourth year during which the House has undergone major repairs and alterations, now totalling nearly $35,000. The previous work has been described in the reports of Mr. Spofford, my predecessor. Except for a possible major expense on the elevator during the next few years, this should complete work to put the House in good condition. From 1912 to 1945, there were no major expenditures of this sort on the House, whose annual outlay never exceeded $3,400. Spreading the major expenses of the last four years over the whole period and including the cost of caretaking, the average cost of maintenance has been $3,855 a year. It was about $2,500 until after World War I, and for next year the amount budgeted is up nearly to $10,000.

However, the $10,000 does not represent a four-fold inflation of maintenance costs from 1912 to 1949, although this accounts for most of the change. The policy of making the House available to other cultural and scientific organizations has increased the operating costs. During the current year thirty-three organizations held 143 meetings with a total attendance of over 11,000. Add to this figure the attendance at the six public exhibits and special meetings under the auspices of the Academy and its School Science Committee, and the total number entering the building comes to over 15,000. This is about double the figure for last year, which was several times that of previous years. Besides the use of the House for meetings and exhibits, outside organizations also continue to share regular occupancy. The Cooperative Broadcasting Council of the Lowell Institute, the Committee on Inter-American Scientific Publication and the Boston Authors Club (the last two being new this year) occupy office space; the Boston Museum of Science and the Boston Authors Club use book-stack space.

The net operating cost of the House is not increased by this increased use of the House, since the various organizations share in these expenses: $3,920.19 this year, $2,403.96 last year, as compared with two or three hundred dollars in past years. The net overhead to the Academy in the future can be still further reduced while providing a much appreciated service to organizations which, in most cases, espouse one or the other of the disciplines embodied in the various classes and sections of the Academy.

The organizations using the House since the last annual meeting were as follows:

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	No. of Meetings
Adult Education Council of Greater Boston	1
Alliance (one meeting with Salon Français)	6
Alpha Phi Sorority, Graduates of Salem Teachers College	1
Amateur Telescope Makers	1
American Association of Museums	2
Antiques Committee, Mass. State Women's Clubs	3
Bond Astronomical Club	1
Boston Authors Club	14
Boston College Institute of Adult Education	9
Boston Post of Society of American Military Engineers	1
Boston Public School Art League	1
Boston School Science Association	1
Boston Society of Civil Engineers	5
Boston Society of Independent Artists	2
Boston Teachers Union	12
Brookline Bird Club	3
Dr. Leonard Carmichael's group	1
Children's Museum Trustees	5
Civil Aeronautics Administration	1
Committee on Rhodes Scholarship	1
Dynamion Society	17
English Speaking Union	2
French Center of New England	8
French Library in Boston	1
Graduate Chapter, Radcliffe Alumnae	1
Institute for Religious and Social Studies	6
Joyce Kilmer Post, American Legion	9
New England Botanical Club	9
New England Council	3
New England Farm and Garden Association	8
New England Section of Optical Society	2
Pan American Society	2
Women's Auxiliary, Norfolk District Medical Society	4
Total	143

The expenditures and appropriations of the House Committee during the fiscal year ending March 31, 1949 were as follows:

Expenditures	
Coal	$ 1,459.02
Gas	20.36
Electricity	1,255.08
Elevator	171.16
Water	57.00
Equipment	337.65

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Supplies and Repairs	$747.43
Fire Insurance	539.96
Custodian and Assistance	2,258.55
Pensions	600.00
Miscellaneous	12.25
Total	$ 7,458.46

Appropriations

House Maintenance, supplies	$ 4,425.00
Custodian and Assistance	2,600.00
Custodian, Pension	600.00
Total	$ 7,625.00
Unexpended	$ 166.54

The special expenditures for repairs and alterations were	$12,929.51
Receipts, Appropriations and Previous Balance totalled	11,129.22
Expenditures exceeded estimates by	$ 1,800.29

In March, 1948, charges for use of facilities were estimated for the fiscal year 1948–1949 at	$ 2,527.00
Actual receipts amounted to	3,636.22
Receipts thus exceeded estimates by	$ 1,109.22

Respectfully submitted,

CHESTER M. ALTER, *Chairman*

May 11, 1949

REPORT OF THE COMMITTEE ON PUBLICATION

The Committee held three meetings during the year and conducted a great deal of business informally.

No books or monographs were published during the year, nor any further numbers of the Memoirs. Eight numbers of the Bulletin, edited by the Executive Officer, appeared from October to May. The Proceedings are now in their 77th volume. Six numbers have been issued, the seventh is in page proof and numbers eight and nine, the last the statutory Summer Number, will be in the mails by August.

This is the first year in which the publication budget has felt the full impact of the inflated printing costs. Of the $9,000 allowed in the budget for 1948–1949, $7,415.05 was spent before the close of the fiscal year on March 31, 1949. Of this total $1,104.13 was for the Bulletin, $6,238.24 for the Proceedings. There is always an overlap as the printer's bills do not come in until a week or

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two after the issues have been mailed, so this year's expenses include two of last year's numbers of the Proceedings. In turn several invoices for issues dated before the end of the fiscal year will be paid from the funds of the new budget. In the year 1948–1949 investment income and sales totalled $5,748.72 to March 31. The reserve balance was therefore reduced from $12,394.48 to $10,728.15. At the present rate of publication this reserve would be wiped out in little more than three years. Income from investment and sales would serve to pay for little more than the Bulletin and the two statutory numbers of the Proceedings.

In view of this crisis in our publication affairs, one which confronts all learned societies, the Publication Committee with the active assistance of the Executive Officer undertook an analysis of costs and a survey of the measures that can be adopted to produce and distribute the Proceedings more economically. A number of minor economies can and will be put into effect in the course of the next year. A major reduction in cost can be achieved only by resorting to other forms of printing. We hesitate to abandon letterpress printing but it is plain that we cannot continue to print everything in that form. One of the numbers to be issued this summer will be composed on the Vari-Typer and printed by the offset process at a saving of $1,300. The Committee will in the future resort to this process for articles with many and complicated tables. The saving is much less and often inconsiderable where straight composition is concerned.

In his last report the Editor appealed to the Fellows for manuscripts. The response was heartening and we trust that papers may continue to come to us at the same rate as in the past year. We have so far been able to publish all that we accepted and we believe we can continue to do so. We can publish, with the help of the indicated economies, from three to four hundred pages annually. We shall continue to announce forthcoming numbers in the Bulletin.

The abnormally large income from sales during the past year was in part due to the post-war purchases of libraries that were completing their files. In considerable measure it was the result of the efforts of our Executive Officer. But an active promotional campaign must await further clarification of our policies.

Respectfully submitted,

TAYLOR STARCK, *Chairman*

May 11, 1949

REPORT OF THE PERMANENT SCIENCE FUND COMMITTEE

The Permanent Science Fund Committee awarded eleven grants-in-aid, for a total of $27,500, during the fiscal year 1948–1949 as follows:

1. To Stanley S. Ballard, Professor of Physics, Tufts College, Medford 55, Mass., for expendable materials, assistance and travel to and from the U. S. Bureau of Standards, in a study of inelastic behavior of optical crystals, $1,900.

2. To Halvor N. Christensen, Professor of Biochemistry, Tufts College Medical School, 416 Huntington Avenue, Boston 15, Mass., toward compen-

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sation of an assistant in studies in cellular concentration of amino acid precursors of protein synthesis, $1,000.

3. To Demarest Davenport, Assistant Professor in Zoology, University of California, Santa Barbara, California, toward expenses for travel and study at Friday Harbor for a study of host-commensal relationships among marine fauna, $400.

4. To William Emerson, Dean Emeritus, School of Architecture, Massachusetts Institute of Technology, for equipment, materials, assistance, travel and other expenses in the preparation for publication of material, gathered in eight years of field study, on changes in the structure of Hagia Sophia since its erection in 537 A. D., for one year, $4,000.

5. To Lewis H. Kleinholz, Associate Professor of Biology, Reed College, Portland 2, Oregon, for a study of nervous regulations of blood sugar levels in crustacea, for materials, assistance and part of travel expense, $450.

6. To R. B. Lindsay, Chairman of the Governing Board, New England School Science Council, 28 Newbury Street, Boston, Mass., to assist the Council in its work for 1948–1949, $2,500.

7. To Robert J. Menzies, Assistant in Zoology, Pacific Marine Station, Dillon Beach, Marin County, California, to enable him to undertake a taxonomic study of the genus Limnoria on the Pacific coast, including examination of test-blocks from that region to be supplied by the Clapp Laboratories of Duxbury, Mass., $1,000.

8. To Norman J. Padelford, Professor of International Relations, Massachusetts Institute of Technology, for a period of two years beginning January 1, 1949, for assistance in preparation for publication for ultimate sale for educational purposes, a series of maps designed to aid in the study of international relations; for the two years, $11,750.

9. To Edmund Schulman, Associate Professor of Dendrology, University of Arizona, Tucson, Arizona, for travel for field study of tree-ring cores in the Andes of Patagonia, $1,500.

10. To Olive Watkins Smith, Director, Fearing Research Laboratory, Free Hospital for Women, 245 Pond Avenue, Brookline, Mass., to aid in a study of estriol tolerance and estrogen metabolism of human cancer, as a supplement to a grant-in-aid from the American Cancer Society, for technical assistance, $1,200.

11. To Virgil P. Sydenstricker, M.D., School of Medicine, University of Georgia, Augusta, Ga., for assistants in his continuing study of changes in cells and tissues in certain dietary deficiencies, $1,800.

The second decennial report of the Permanent Science Fund Committee is in press.

Respectfully submitted,

JOHN W. M. BUNKER, *Chairman*

May 11, 1949

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REPORT OF THE RUMFORD COMMITTEE

Six grants-in-aid of research have been made during the year 1948–1949 as follows:

To Dr. Otto Glaser of Amherst College, $250, to help pay for spectroscopic measures needed in the course of his researches on mineral metabolism in Fundulus eggs and copper traffic in Ascidian larvae.

To Professor R. F. Daubenmire of the State College of Washington, $500, to enable him to purchase two hygrothermographs with louvered shelters, to be used in an ecological study of the distribution of forest types in the northern Rocky Mountains.

To Dr. Harold Scheraga of Cornell University, $800, towards the expenses of acquiring special optical equipment for the study of double refraction produced in solutions of macromolecules by external electric fields. His application was supported by letters from Professors Debye, Bauer, and Long, all of Cornell University.

To Dr. Donald C. Stockbarger, Associate Professor of Physics, Massachusetts Institute of Technology, $750, to be applied to the purchase of a polarizing microscope for his researches on optical crystals.

To Dr. Cecilia Payne-Gaposchkin, Lecturer in Astronomy in Radcliffe and in the Harvard Graduate School, and Phillips Astronomer in the Harvard Observatory, $750, towards a total of $1,500 for the construction of a photoelectric photometer and the adaptation of a 24-inch reflector for researches in her field of a stellar variation and stellar evolution, conditioned upon remainder being secured from another source.

To Dr. Stanley S. Ballard, Professor of Physics, Tufts College, $500, towards the design and construction of apparatus for measuring the thermal conductivity of small samples of poorly conducting materials such as optical crystals.

The Committee recommended, and the Council approved, the award of the Rumford Premium for 1949 be made to Dr. Ira S. Bowen, Director of the Mount Wilson and Palomar Observatories in California, for his solution of the mystery of nebulium and for other outstanding work in spectroscopy.

The Assistant Treasurer of the American Academy reports a balance on hand on March 1, 1949, of $22,473.79.

The estimated investment income for 1948–1949 is $4,780. The total available for appropriation is $27,253.79.

Respectfully submitted,

HARLOW SHAPLEY, *Chairman*

May 11, 1949

REPORT OF THE CYRUS M. WARREN COMMITTEE

The Committee had available for grants the sum of $1,200, the amount voted by the Council at the meeting on March 10, 1948, for awards during the year 1948–1949.

At a meeting of the Committee on May 18 the following grants were voted:

To Doctor Charles L. Bickel of the Phillips Exeter Academy, a grant of

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$100 for supplies needed to carry on further research in organic chemistry, for which a grant of $150 had been made in October, 1947.

To Professor A. E. Martell of Clark University, Worcester, a grant of $300 for equipment needed to carry on research on conductivities of non-aqueous solutions, for which a previous grant of $300 had been made a year ago.

To Professor Pierre Van Rysselberghe of University of Oregon, a grant of $325 for special items of equipment to be used in continuing his polarographic research, for which previous grants had been made in 1944, 1945 and 1946.

A letter was received from Professor E. R. Atkinson of the University of New Hampshire reporting on the progress of research which was assisted by a grant in 1946. The research is being continued.

Letters of appreciation for the grants made to Professor Van Rysselberghe were received from the President of the University of Oregon and from the Secretary of the State Board of Higher Education.

Reprints have been received as follows:

Melting Point Curves of Optical Isomers by C. L. Bickel and Alfred T. Peaslee, Jr., J. Am. Chem. Soc., *70*, 1790 (1948).

Beta-Alkoxy Derivatives of 2-Chlorochalcone by C. L. Bickel, J. Am. Chem. Soc., *71*, 336 (1949).

An Improved Conductance Bridge by W. L. Fox and A. E. Martell, Rev. Sci. Instr. *19*, 628 (1948).

Respectfully submitted,

May 11, 1949 FREDERICK G. KEYES, *Chairman*

REPORT OF THE AMORY PRIZE COMMITTEE

The Amory Prize Committee met on October 6, 1948, and made arrangements concerning the December 8 meeting of the Academy when the awarding of the Amory Prizes for the septennium ending November 10, 1947, would take place.

At the Academy meeting, December 8, 1948, an engrossed citation and a check for $3,500 were presented to each of the awardees of the Amory Prize for the second septennium, as follows:

To Alexander Benjamin Gutman, of New York City, New York, for his demonstration, aided by his late wife, E. B. Gutman, of the usefulness of serum acid phosphatase determination in the diagnosis and management of patients with prostatic malignancy.

To Charles Brenton Huggins, of Chicago, Illinois, for his studies on the prostate gland, on the influence of several hormones on prostatic secretion, and on the diagnosis and treatment of cancer of the prostate which have brought relief to many men.

To Willem Johan Kolff, of Kampen, The Netherlands, for his development of an artificial kidney in the treatment of patients with uremia and for his monograph describing the construction of the apparatus, indications for its use, and observations on its effectiveness.

To Guy Frederic Marrian, of Edinburgh, Scotland (represented by Mr. C. E. Whitamore, British Consul General at Boston), for his researches in the

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chemistry, biochemistry, and metabolism of the steroid hormones affecting the activity of the male and female generative tract, leading to important diagnostic and therapeutic measures.

To Mr. George Nicholas Papanicolaou, of New York City, New York, for his development of exfoliative cytology and its application to rapid and simple methods of diagnosis of cancer of the organs of the genitourinary tract.

To Selman Abraham Waksman, of New Brunswick, New Jersey, for his discovery of streptomycin, an antibiotic agent which has proved to be of great value in the treatment of infections common to the urinary passage.

Dr. Charles B. Huggins addressed the Academy on "Medical Significance of the Amory Prize Researches."

The Committee met on December 8, 1948, together with the Amory Prize recipients for 1941 and 1947, to consider how to select Amory Prize awardees of the third septennium.

Respectfully submitted,
EDWIN B. WILSON, *Chairman*

May 11, 1949

The annual election of officers and committees was held. The Fellows proposed by the Nominating Committee were elected to office as follows:

Howard M. Jones . . . . . *President*
Roland G. D. Richardson . . . . . *Vice-President for Class I*
Irving W. Bailey . . . . . *Vice-President for Class II*
Robert B. Stewart . . . . . *Vice-President for Class III*
William A. Jackson . . . . . *Vice-President for Class IV*
John W. M. Bunker . . . . . *Secretary*
Horace S. Ford . . . . . *Treasurer*
Ernest H. Huntress . . . . . *Librarian*
Taylor Starck . . . . . *Editor*

COUNCILLORS TO SERVE FOR FOUR YEARS

Edwin H. Land, *of Class I*
Francis O. Schmitt, *of Class II*
W. Rupert Maclaurin, *of Class III*
George W. Sherburn, *of Class IV*

COUNCILLOR TO SERVE FOR THREE YEARS

Henry R. Viets, *of Class IV*

HOUSE COMMITTEE

Chester M. Alter, *Chairman*

Charles H. Taylor
John B. Wilbur

COMMITTEE ON MEMBERSHIP

The President, *Chairman, ex officio*

To serve for two years

Kenneth T. Bainbridge, *of Class I*
Samuel A. Levine, *of Class II*
Erwin D. Canham, *of Class III*
Wilbur K. Jordan, *of Class IV*

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To serve for one year

Arthur N. Holcombe, *of Class III*

COMMITTEE ON MEETINGS

The President, *Chairman, ex officio*
The Four Vice-Presidents, *ex officiis*
The Secretary, *ex officio*

William Emerson — Erwin H. Schell
Henry B. Phillips — George Wald

COMMITTEE ON FINANCE

The Treasurer, *Chairman, ex officio*

Ralph E. Freeman — Henry P. Kendall
Jerome C. Hunsaker — Henry L. Shattuck

AUDITING COMMITTEE

Thomas H. Sanders — Donald S. Tucker

COMMITTEE ON PUBLICATION

The Editor, *Chairman, ex officio*

Ernest H. Huntress — Kenneth V. Thimann
Kenneth B. Murdock — Thomas North Whitehead

PERMANENT SCIENCE FUND COMMITTEE

Hudson Hoagland, *Chairman*

Gustavus J. Esselen — Edward L. Moreland — Talcott Parsons
A. Baird Hastings — Frederick K. Morris — Julius A. Stratton

RUMFORD COMMITTEE

Harlow Shapley, *Chairman*

Percy W. Bridgman — George R. Harrison — Edwin H. Land
Arthur C. Hardy — Joseph H. Keenan — Francis O. Schmitt

C. M. WARREN COMMITTEE

Frederick G. Keyes, *Chairman*

Edwin J. Cohn — Charles A. Kraus — Avery A. Morton
Louis F. Fieser — Eugene M. Landis — Walter C. Schumb

AMORY PRIZE COMMITTEE

Edwin B. Wilson, *Chairman*

William B. Castle — Gregory Pincus — George B. Wislocki
Roy G. Hoskins — George W. Thorn — S. Burt Wolbach

New Fellows and Foreign Honorary Members were elected to the Academy as follows:

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FELLOWS

Class I, Mathematical and Physical Sciences

Section 1, Mathematics and Astronomy

Lars Valerian Ahlfors . . . . . Cambridge
Witold Hurewicz . . . . . Cambridge
Gerard Peter Kuiper . . . . . Chicago, Ill.

Section 2, Physics

Jesse Wakefield Beams . . . . . Charlottesville, Va.
James Brown Fisk . . . . . Cambridge
Nathaniel Herman Frank . . . . . Cambridge
Wendell Hinkle Furry . . . . . Cambridge
Hans Mueller . . . . . Cambridge
Jerrold Reinach Zacharias . . . . . Cambridge

Section 3, Chemistry

William Clouser Boyd . . . . . Boston
John Gamble Kirkwood . . . . . Pasadena, Cal.
James Joseph Lingane . . . . . Cambridge
Fritz Albert Lipmann . . . . . Boston
John Howard Northrop . . . . . Princeton, N. J.
Lars Onsager . . . . . New Haven, Conn.
Eugene George Rochow . . . . . Cambridge
Wendell Meredith Stanley . . . . . Berkeley, Cal.
James Batcheller Sumner . . . . . Ithaca, N. Y.

Section 4, Technology and Engineering

Arthur Casagrande . . . . . Cambridge
Edward Lull Cochrane . . . . . Cambridge
Arthur Thomas Ippen . . . . . Cambridge
John Torrey Norton . . . . . Cambridge
Charles Fayette Taylor . . . . . Cambridge
Edward Story Taylor . . . . . Cambridge
Hsue-Shen Tsien . . . . . Cambridge

Class II, Natural and Physiological Sciences

Section 1, Geology, Mineralogy, and Physics of the Globe

Wilmot Hyde Bradley . . . . . Washington, D. C.
Walter Herman Bucher . . . . . New York, N. Y.
Clifford Frondel . . . . . Cambridge
James Gilluly . . . . . Los Angeles, Cal.
Hugh Exton McKinistry . . . . . Cambridge

Section 2, Botany

Lawrence Rogers Blinks . . . . . Pacific Grove, Cal.
Jens Christian Clausen . . . . . Stanford University, Cal.
Katherine Esau . . . . . Davis, Cal.

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Kenneth Bryan Raper . . . . . Peoria, Ill.
Reed Clark Rollins . . . . . Cambridge
Lewis John Stadler . . . . . Columbia, Mo.
Selman Abraham Waksman . . . . . New Brunswick, N. J.

Section 3, Zoology and Physiology

Edwin Bennett Astwood . . . . . Boston
Edward Wheeler Dempsey . . . . . Boston
George Evelyn Hutchinson . . . . . New Haven, Conn.
Otto Krayer . . . . . Boston
Cyril Norman Hugh Long . . . . . New Haven, Conn.
John Spangler Nicholas . . . . . New Haven, Conn.
Homer William Smith . . . . . New York, N. Y.
Tracy Morton Sonneborn . . . . . Bloomington, Ill.
Alfred Henry Sturtevant . . . . . Pasadena, Cal.
James Walter Wilson . . . . . Providence, R. I.

Section 4, Medicine and Surgery

Herrman Ludwig Blumgart . . . . . Boston
David Glendenning Cogan . . . . . Boston
Sidney Farber . . . . . Boston
Harry Sylvestre Nutting Greene . . . . . New Haven, Conn.
Robert Edward Gross . . . . . Boston
Arthur Tremain Hertig . . . . . Boston
Charles Brenton Huggins . . . . . Chicago, Ill.
Robert Frederick Loeb . . . . . New York, N. Y.

CLASS III, THE SOCIAL ARTS

Section 1, Jurisprudence

John Cobb Cooper . . . . . Princeton, N. J.
Charles Antone Horsky . . . . . Washington, D. C.
Phillips Ketchum . . . . . Boston

Section 2, Government, International Law, and Diplomacy

Leland Matthew Goodrich . . . . . Providence, R. I.
Walter Lippmann . . . . . Washington, D. C.
Henry Cabot Lodge, Jr. . . . . Washington, D. C.

Section 3, Economics and Sociology

Pendleton Herring . . . . . New York, N. Y.
Philip Taft . . . . . Providence, R. I.

Section 4, Administration and Affairs

Bancroft Beatley . . . . . Boston
S. Bruce Black . . . . . Boston
Lloyd DeW. Brace . . . . . Boston
Detlev Wulf Bronk . . . . . Baltimore, Md.
Oliver Ellsworth Buckley . . . . . New York, N. Y.

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Paul Foster Clark . . . . . Boston
John Wells Farley . . . . . Boston
Harold Daniel Hodgkinson . . . . . Boston
Louis Martin Lyons . . . . . Cambridge
Eugene Meyer . . . . . Washington, D. C.
Arthur Grinnell Rotch . . . . . Boston
George A. Sloan . . . . . New York, N. Y.
Carroll Louis Wilson . . . . . Washington, D. C.

Class IV, The Humanities

Section 1, Theology, Philosophy, and Psychology

Millar Burrows . . . . . New Haven, Conn.
Reinhold Niebuhr . . . . . New York, N. Y.
DeWitt Henry Parker . . . . . Ann Arbor, Mich.
Willard Van Orman Quine . . . . . Cambridge
Edward Chace Tolman . . . . . Berkeley, Cal.

Section 2, History, Archaeology, and Anthropology

Julian Parks Boyd . . . . . Princeton, N. J.
Gilbert Chinard . . . . . Princeton, N. J.
Merle Curti . . . . . Madison, Wis.
Mason Hammond . . . . . Cambridge
James Blaine Hedges . . . . . Providence, R. I.
Kenneth Scott Latourette . . . . . New Haven, Conn.
Richard Harrison Shryock . . . . . Philadelphia, Pa.

Section 3, Philology

Oscar James Campbell, Jr. . . . . New York, N. Y.
Archer Taylor . . . . . Berkeley, Cal.
Louis Booker Wright . . . . . Washington, D. C.

Section 4, The Fine Arts and Belles Lettres

Van Wyck Brooks . . . . . Bridgewater, Conn.
Robert Peter Tristram Coffin . . . . . Brunswick, Me.
Bernard Augustine De Voto . . . . . Cambridge
William Addison Dwiggins . . . . . Hingham
Esther Forbes . . . . . Worcester
Jack Levine . . . . . New York, N. Y.
Thomas Mann . . . . . Pacific Palisades, Cal.
Lucien Price . . . . . Boston

FOREIGN HONORARY MEMBERS

Class I

Section 3, Chemistry

Chaim Weizmann . . . . . Tel Aviv

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CLASS III

Section 2, Government, International Law, and Diplomacy

Sir Alfred Zimmern ..... London

CLASS IV

Section 2, History, Archaeology, and Anthropology

Arnold Joseph Toynbee ..... London

Section 4, The Fine Arts and Belles Lettres

Oscar Niemeyer ..... Rio de Janeiro
Levin Ludwig Schuecking ..... Farchant, Germany

The following communication was presented:

Parker Wheatley: *Radio and Television as Instruments of Education.*

The meeting was dissolved at 10:15 P. M.

REPORT OF THE EXECUTIVE OFFICER TO THE PRESIDENT

On March 21 last, I reported to you on the several categories of work performed by the Academy office, how much each one cost, and how these actual operations compared with the recommendations of the Commission on the Present Status and Future of the Academy concerning the functions of an executive officer. Here I endeavor to report briefly on what has been accomplished through these operations in the light of the general objectives set by that Commission.

In brief, it was the thesis of the Commission that the focus of an inclusive learned society today cannot be so much on the advancement of research and knowledge in each of the many specialized disciplines as on the "humanization" of knowledge—the revealing of the significance of knowledge for the life of man. It proposed that capital should be made of the diversity of areas of scholarship represented in the Academy membership, as well as its high level, in an attempt to synthesize knowledge for the welfare of the community, particularly the New England community. The Commission's specific suggestions for implementing this function constitute the chart which has guided the Academy's path since their publication in 1946.

It was the opinion of the Commission that in order for the Academy to function properly as a dynamic institution, "administration should be concentrated in the hands of a competent executive officer, assisted by an office secretary who would be on duty regularly in an office located on the first floor of the building close to the main entrance." This nerve center for Academy action and reaction has been provided, and communication channels with the various affectors and effectors have been fairly well established. Officers, committee chairmen, Fellows, and outsiders press buttons and the organization reacts in a more or less integrated fashion along the lines set by the policies established.

Without any precedent, the office had to feel its way around among the various processes of the organization and gradually establish some working

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relation. It has been found that although there is a large amount of fairly regular routine operations to be accomplished, there are sudden variations in demand for services, variable both as regards quantity and quality; and a staff of some four or five persons has been developed to take care of this need for flexibility. Also, while the office is primarily a passive instrument for executing specific orders from the several centers of Academy authority, and the Executive Officer is not "a policy-making official," the office, as a nerve center, has made itself constitutionally sensitive to stimulation from the environment or from within the organization in any matters that might have pertinency for the Academy's self-fulfillment in the direction recommended by the Commission. These stimuli are fortified and passed on to the appropriate committees or officers and sometimes result in a new project, and thus in a sense the office serves as an instrument of creativity.

There is perhaps little point in indicating the routine services rendered by the office, except to point out that the requirements of four active officers and a dozen functioning committees keep three or four of us busy in the office, in addition to the custodian and his assistant. In brief, as was indicated in the previous report, over half the labors of the office have been concerned with the recording of the acts of the meetings of the Academy, its Council, and its standing committees, and the execution of the orders of these bodies and their officers. The carrying on of operations for the President, Secretary, Treasurer, and Librarian took about one-fifth of our time, or about $1,600 worth; operations for the standing committees consumed about one-half of our efforts, or about $4,000; and special committees consumed about thirty per cent, or $2,400.

Specific mention should be made of activities which represent new functions of the Academy in fulfillment of the recommendations made by the Commission on the Present Status and Future of the Academy. These center in the work of certain committees and are briefly discussed in the paragraphs below. About seventy per cent of the time of the office staff has gone into the work of these committees, and progress has been made on practically every suggestion of the Commission.

In the case of the functions centering on the use of the building at 28 Newbury Street, the office has served as the agent of the House Committee in arranging with the architect for alterations and renovations to carry out the Mather Commission's recommendations, and in supervising the actual carrying out of these: an exhibit hall and offices on the first floor, a conference room and snack kitchen on the third floor, new offices for outside organizations on the fourth floor, a new roof, and several minor projects. The designation of the House as a mausoleum because it was dark, dusty, and undisturbed except by eight invasions a year of about 50 Fellows, is hardly applicable now. Some 11,000 attend meetings here of various scientific and cultural organizations of the community, and about 4,000 attend exhibits or other functions sponsored directly by the Academy. Instead of daily occupancy by a sole librarian with a handful of visitors in a year, there are over a dozen persons busy in the offices with many visitors each day. The several recommendations of the Commission on the use of the House by the Academy and by outside

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organizations are being carried out, and the funds invested in this real estate are yielding a much higher percentage of value for the encouragement of the arts and sciences in our community.

For the Committee on Meetings, an analysis was made of the attendance at meetings over a 35-year period, in relation to subject, speaker, and season. Various suggestions have been made to make the meetings of interest more broadly among the Fellows in line with the recommendations of the Commission. Meetings of committees, seminar-type groups, conferences, and symposia have been developed, and plans for more are under way.

For the Committee on Publication, the Bulletin has been established and published eight times a year. A detailed analysis of the character, distribution, and costs of the Proceedings and their relation to available funds was made. The Committee has taken steps to reduce costs and otherwise improve the financial position of the Proceedings, and is making long-range plans to keep the Proceedings a significant serial in the arts and sciences.

Among the special committees, that on School Science has taken the greatest amount of effort on the part of the office, which has been the focal center for the several programs of the Committee for the stimulation and improvement of science education in the secondary schools. The largest of these programs, so far, is the development of science fairs in schools generally throughout New England and an annual regional finals for local winners held at the Academy. This movement doubled in size during its second year, when a school population of over 200,000 was involved. In the local communities the interests of students, parents, teachers and school officials in the problems of science education were increased. Another project is one that is focussing attention on atomic science and its place in the secondary school curriculum. A four-day gathering of science teachers from the New England states last December has given rise to a continuing committee, a bulletin, and a series of local atomic science workshops in different states. Another project is one which is stimulating a more direct interconnection between New England industries and the products they receive from the secondary schools in the form of manpower. Enthusiasm of science teachers for their work has been aroused and their viewpoints are broadened by the inauguration of a series of specially conducted tours of industrial plants to see applications of science in the economic powerhouses of their own neighborhood. All these activities can lead to a more adequate curriculum, better teachers and teaching methods, increased interest and efficiency of the pupil, with better preparation for citizenship and career in the atomic age. This project is an experiment which embodies several of the recommendations of the Commission on the Present Status and Future of the Academy, such as putting knowledge into the service of the New England community, influencing and enlightening public opinion, improving educational, occupational, and industrial opportunities, cooperating with other agencies, academic and otherwise, using the House for symposia, conferences, exhibits, meetings, and providing an office for administration of the program.

Acting on behalf of the Committee on Cultural and Scientific Societies of Metropolitan Boston, the office is in the midst of a survey of such organizations and the preparation of a directory of them. Through the work of this Com-

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mittee, the Academy is giving general support to the scientific and cultural organizations of our local community and pointing up the possibility of co-operative solution of many common problems of these "daughter" societies, particularly in such matters as publication, housing, and general operations.

Other committees have been served in such activities as the organization of conferences, on problems of aging, the program of the United Nations Educational, Scientific and Cultural Organization in the humanities; symposia on the present state of medical knowledge of poliomyelitis and medical care and the public. One case of an attempt to illumine and influence public opinion was the work of the Committee on the Condon Case, which investigated the situation, made a statement, and presented to the public the results of a poll of the Fellows on the statement. Seven public exhibits were held in the lobby: on polarization of light, microscopy of a drop of water, poliomyelitis, acoustics, astronomy, book publishing, and architecture.

The office in all of its activities has been conscious of the problem of building proper public understanding of the nature and services of the Academy, since ultimately all institutions depend on the attitude of the community they serve and the support received from it. In both personal contacts and material for publication, efforts have been made to make clear the nature of the Academy as a high-level organization of scholars serving the community by means of its particular genius.

The expenditures of the general funds of the Academy, in the last year amounting to over $36,000, was administered with care as to effective use and as to budgetary limits, the expenditures being a few per cent under one hundred per cent of the allotments for Salaries, House Maintenance and General Administration, and a few per cent over for the Special Alterations. Cost analyses have been made of house, publishing and other operations in the light of which recommendations have been made for greater economy or effectiveness.

Lest it be mistakenly conceived that major credit for the Academy's administration go to the office, it should be pointed out that the office has been primarily engaged in carrying out the orders and policies of officers and committeemen, many of whom have spent such an amount of time and effort as is probably scarcely conceived of by the membership in general. The dependence of the vitality of the Academy upon the labors of the President, Secretary, Treasurer, and Editor especially should be more broadly appreciated; and one should not overlook the lesser but nevertheless considerable time devoted by the councillors and committeemen. The Executive Officer must make personal acknowledgment of the invariable friendliness and helpfulness of all officers and members with whom he has had dealings. They have made his path smooth and pleasant.

The Executive Officer must point out also that he is only one in a loyal, able and integrated unit of four or five servants of the Academy. I believe it is seldom a man's privilege to have more cooperative or effective teammates than our Office Secretary, Priscilla Bunker, and our Custodian, Harry Waters. Nor do I overlook the faithful and friendly services of our Office Assistant, Berry Delahanty; of Alice Waters, wife and helper of the Custodian; of Mrs.

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Ball, our retired Assistant Librarian, who still comes in to help out from time to time; and other occasional assistants, and from the Treasurer's office, at M. I. T., Wolcott Hokanson has given us his helpful and friendly cooperation in all matters fiscal. I am happy indeed that it has been possible to get together such a congenial and yet efficient group to take care of the routine operations of the Academy.

Respectfully submitted,

RALPH W. BURHOE, *Executive Officer*

May 11, 1949

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